Proceedings of the
XIIth International Symposium on Biomechanics
and Medicine in Swimming

28 April to 2 May 2014

Australian Institute of Sport, Canberra
Preface

Biomechancis and Medicine in Swimming. 44 Years of Swimming Science.

The organising committee for BMS2014 is proud to welcome the delegates of the XIIth International Symposium for Biomechanics and Medicine in Swimming. It is an honour for us as the organising committee, for the Australian Institute of Sport, for Swimming Australia and for the John Curtin School of Medical Research to host this unique conference and to provide this Book of Proceedings as a hard copy record of presentations. We believe that BMS XII provides access for aquatic investigators, technicians, practitioners and coaches to the advances in aquatic science and medicine since BMS 2010 in Oslo.

The International Symposium for Biomechanics and Medicine in Swimming remains the most prestigious of all international aquatic oriented scientific congresses. It has also retained its' high ideal of the peer review process, that is essential to scientific progress. Every submission has had the benefit of expert critique. Twelve times now, BMS has presented cutting edge research in a variety of disciplines and aquatic sports. Each time the challenge has been to present the best possible overview of the most important developments in the four year period since the previous BMS symposium.

The first symposium was held in Brussels in 1970 and it has now been held in eleven different countries and on both sides of the Atlantic. This conference is the first BMS symposium to be held in the southern hemisphere and in the Australasian region. BMS has a unique place in sport science and medical research dealing with the aquatic sports and has a proud tradition. The series of twelve published BMS Proceedings books has formed the backbone of literature in aquatic research for over four decades. These are a collection of peer reviewed scientific papers commanding considerable respect and as such serves as a valuable resource for all who are interested in keeping up to date with aquatic research. While the majority of papers at BMS2014 lie within biomechanics, then physiology followed by medicine, other disciplines are also represented including nutrition, the social sciences and pedagogy. Because of the expertise in the Australian Institute of Sport and Australian Swimming, coaching has been included as a separate distinct discipline in BMS2014.

The first edition of the proceedings (1971) gathered an intellectually rich mixture of the early pioneers, the established researchers and young, aspiring investigators. It read like the Who’s Who of aquatic research, including the pioneers T.K. Cureton Jr. who already in 1930 had published a biomechanical analysis of the crawl kick. It also included established researchers of the day such as Dr James ‘Doc’ Counsilman who introduced us to Bernoulli’s principle as a possible explanation for propulsion in swimming and Dr Per-Olof Astrand who introduced the first swimming flume. Dr Leon Lewillie, Dr Barthels and Dr Adrian introduced underwater electromyography to the delegates. Dr Mitsumasa Miyashita and Dr Richard Nelson presented, at that time, sophisticated analyses of the crawl.

The BMS2014 Symposium includes 74 poster presentations, 115 oral presentations overall, two workshops and two poolside demonstrations are provided for the coaching stream and four poolside demonstrations for the general conference delegates. Also, eleven keynote speakers presented outstanding lectures to the audience. The keynote speakers were Senior Coach Bill Sweetenham and Dr Andrei Vorontsov in the coaching stream, Dr Frank Fish and Dr Raymond Cohen (CFD) in the biomechanics area, Dr Phillippe Hellard in physiology, Professor David Costill in nutrition, Professor Peter Fricker in medicine, Peter Blanch in physiotherapy, Professor Stephen Langendorfer in the social sciences and Professor Robert Newton in strength and development.

These contributions ensure that the essence of our conference series is passed on, and these presentations provide the current research in their respective fields. In honour of the BMS
community’s 44th anniversary, the first paper in this book is from Professor JP Vilas-Boas and is entitled “Building up” in Swimming Science.

The 98 papers in this book are organised into 7 different chapters, reflecting each paper’s scientific discipline. We take also this opportunity to thank all of the authors who contributed to these papers. Their contribution often represents months of work, sometimes years. It builds on a lifetime of experience and a collegial exchange of ideas, often these days, across international borders. Only the six page papers of the oral podium presenters together with those of the keynotes are included within these proceedings.

The BMS2014 Symposium would not have been possible without our partners, exhibitors and sponsors. We thank our partners, the Australian Institute of Sport, Australian Swimming and the John Curtin school of Medical Research. This kind of contact between BMS and practitioners ensures that aquatic science adapts to applied situations. We would also like to thank the sponsors and exhibitors: Kistler, Contemplas, Cortex, Cosmed, 2XU, the Australian Institute of Sport and the ACT Government for their contribution in making BMS2014 possible.

The volunteers are thanked for making BMS2014 a memorable conference. We hope you, in the midst of your hard work, gained valuable experience as well as enjoyable moments. The Scientific Review Committees, the Discipline Coordinators and the Organising committees over the last four years provided an extensive effort in preparing for this conference. We thank you greatly for your contribution. We thank also the International Steering Group of BMS for providing expert advice and for providing the continuity which has made 44 years of BMS possible. Finally we wish to honour the Australian Institute of Sport for providing financial and administrative support as well as providing the use of symposium venues including the presentation venues, the workshop venues, the pools, the delegate recreation facilities and the meeting and meal areas, free of charge. In particular members of the AIS Sport Science and Medicine area ensured the success of the conference by supporting all those with specific responsibilities associated with the conference preparation. Finally this book would not have been a reality without the editorial assistance of Gina Shaw and Nicole Murphy from Conference Logistics, Debbie Phillips (DP Plus), AIS Communications for the covers and LC Digital for the printing.

We hope you will enjoy reading the contributions of this fine congress!

Bruce Mason  Dale Barnes  David Jukes  Nicole Vlahovich
Canberra, April 2014
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1 Invited lectures

THE LEÓN LEWILLIE MEMORIAL LECTURE 2014

‘Building up’ in swimming science

João Paulo Vilas-Boas 1,2,3

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The BMS movement emerged from the Steering Group Biomechanics and Medicine in Swimming of the World Commission of Sciences and Sports (International Council of Sport Science and Physical Education – ICSSPE – UNESCO), aiming to promote the production, spreading and recognition of science within the sports community, particularly in swimming. Over the last 30 years, the University of Porto, Portugal, has been fighting for this goal, despite initiating and evolving this purpose in a particularly adverse context, as follows: (i) a small peripheral country; (ii) little expression of the swimming sport; (iii) far from leading other sport sciences on a global scale; (iv) low confidence on scientific and theoretical ‘external’ contributions to the field of swimming practice, and (v) limited budget and staff. Sport and science ‘entrepreneurs’, like León Lewillie (and also Jean-Peter Clarys), and the BMS family, catalyse that fight over time, through their example and the opportunity and motivations they have made possible. Nowadays, the University of Porto, the Faculty of Sport, the Porto Biomechanics Laboratory, and especially the Swimming Science Portuguese family, may be proud of a raised building. This text explores the story behind this ‘locally based struggle for the BMS spirit’, concluding that projects like this one are feasible, and may also be a word of motivation for the sake of their proliferation throughout the world.

Keywords: swimming science, practice, research, development strategy, innovation, biophysics

Introduction

León Lewillie was a passionate person—passionate by sport, particularly in swimming and water-polo, but also in technology, art, and human progress. Perhaps because of that, he was one of the pioneers of swimming research in the world, particularly in Europe. These combined interests allow us, every four years, at the Biomechanics and Medicine in Swimming – BMS – conference, to remember him also as the entrepreneur of the BMS conference and world movement that underpin the Steering Group. Nevertheless, León Lewillie was not alone in this specific accomplishment. Indeed, J.-P. Clarys, the distinguished anatomist and swimming biomechanicist, co-organised the first and the second BMS (at the time named ‘Biomechanics in Swimming’) symposiums in Brussels (1970 and 1974), being Lewillie’s right-hand man in these historical happenings. Neither León nor Jean-Peter can be considered common persons: They were and are constructors—uncommon builders of new, unsuspected and unexpected realities that have an eternal impact on the community. Both were, indeed, builders of a unique movement: the Biomechanics and Medicine in Swimming. This movement gathers, every four years, the Swimming Science family, one of the most—if not the most—productive sport-specific scientific communities in the world. León and Jean-Peter were (and fortunately Jean-Peter still is) both like the mythic (but at the same time very real) medieval cathedral builders who build marvellous buildings created to last for ever, based on the most modern ideas and technology, while respecting the ancestral knowledge and traditions. In my opinion, we all have to pay our tribute to both, following their example: (i) we have to dare to build; (ii) we must respect and honour the seminal traditions; (iii) we should build to grow mankind, while transferring knowledge and
developing practice; (iv) we need to rely on the most modern incomes; (v) we must cooperate and celebrate friendship; and (vi) we need to think big, far, and lasting.

I believe that this is the culture and the tradition of BMS. This is what I learned over the years, particularly after receiving the honour of integrating the Steering Group, and is the main inspiration for my daily work. Humbly, not comparable, but inspired by, I also fight, day by day, to build up a research group, a teaching group, and a science-to-practice transferring group! I desire to be a builder of a marginal positive scientific reality in a country of very asymmetrical science; a builder of a sport-specific recognised scientific pole other than football—in a country of footballers; a builder of a research community that may catalyse a national underdeveloped sport; a builder of a leadership project in a country that does not seem to be able to lead itself.

The purpose of this paper, therefore, is to present a testimony; a testimony of a tentative-building inspired by the BMS movement and family, and especially in the basilar personalities of León Lewillie, and Jean-Peter Clarys. This building was to be a swimming science centre in Porto, Portugal, a peripheral scientific country of the world, and a country far from leading swimming sport. I want to apologise for this presumptuous purpose; nevertheless, I would like to state from the beginning that this is an exercise far from being narcissist in nature; on the contrary, it is dedicated to honour those who made and still make this project possible: a very large working team (nowadays co-headed by Ricardo Fernandes), and a number of inspirational scientific personalities that gave us the honour of actively participating in our efforts. Moreover, it is devoted to further motivate similar initiatives that converge to fulfil the aim of the World Commission of Sciences and Sports: to promote science in sport!

**Background**

Swimming science interest, in Portugal, is not recent. At the first and second BMS conferences, there were Portuguese representatives among the participants. João Abrantes, who was a swimming coach, and a biomechanicist (like myself some years latter), was the first to enter this community. He merged two of the main requirements (to be a practitioner and/or a scientist) to follow one of the most relevant BMS aims: ‘bridging the theory to practice gap’. I remember that this was the ‘slogan’ of a meeting organised by the KUL, in Leuven, Belgium, in the winter of 1986 (chaired by Ulrik Persyn, and organised by Daniel Daly, Luc van Tilborgh, and Veronique Colman), just after BMS V in Bielefeld (where KUL’s van Tilborgh et al. 1988, won the Archimedes Award). That meeting was my first serious direct contact with the international scientific swimming community, in which high technology was applied to sport. Here, computer-based expert systems support evaluation (anthropometry, force, flexibility, physiology and biomechanics) and sport-specific advice (Persyn et al. 1984, 1988). At that time I was really impressed and still am! For this reason I think that this is the ideal opportunity to also honour Ulrik Persyn, his group and the unforgettable ‘building’ they left behind (please let me also underline here the name of Veronique Colman, also an Archimedes Award winner, and a friend that will live forever). Interestingly, 1986 was also the year of the First World Swimming Coaches Congress, held in Madrid, just before the World Swimming Championships. Indeed, it was during that event that I clearly perceived a huge gap between swimming coaching and science at a global level (not only in Portugal), a gap which was imperative to bridge. I remember the USA coaches’ round table and the American ‘X factor’ for talents selection, as well as the surprising Pablo Morales’ training programs, particularly considering the ‘in the mood’ strategy to define specific butterfly training sessions!

1986 was definitively the year of my choice. Once coaching practice and science were quite different territories, with a huge future potential if combined, so I choose to attempt at merging or articulating them. Passionate about coaching practice (which I extended until the 2004 Olympic Games), I decided to concomitantly invest in science, experiencing a dual strategy solution in the global swimming world.
In 1990, in Liverpool, I join the BMS family for the first time, following an unforgettable BMS Satellite Meeting again organised by Ulrik Persyn and co-workers in Leuven, Belgium. Since then, BMS conferences have continued to be my main anchor, my inspiration, my target. This commitment got stronger in 2002, in Saint-Étienne, France (BMS chaired by Jean-Claude Chatard) when it was given to the University of Porto the privilege of hosting the meeting in 2006, and also during the 2006 BMS itself. In addition, my involvement with BMS was strengthened when, after 2006, I became a member of the Steering Group Biomechanics and Medicine in Swimming.

The University of Porto Strategy

1986 and 1990, two BMS conferences and one BMS cycle, changed my world. I started dreaming about being a swimming coach, and progressively, I decided to become a scientist but a coach-scientist and, if possible a coaching-relevant scientist (nothing less...). Those were the golden years of the ‘everything is possible in life’ mentality. Indeed, at that time, I was coaching a Portuguese third-division team, and we had no specific or dedicated research facilities at the University of Porto’s Faculty of Sport. However, I was obsessed with starting swimming-scientific research with practical relevance, despite being quite solitary.

Vision

Passionate about research, addicted to training, and enthusiastic about modernity and development, I imagined (at the ‘far-West’ corner of Europe) that we could pursue excellence, and particularly, that we could do it by connecting swimming training practice and swimming knowledge and research. I was a coach, a university teacher, and, potentially, also a researcher, so, why not merge all those avocations together? Why not build them as fractals, each and all of them incorporating the integral complexity of the emerging system (science + teaching + coaching practices) in a coherent outcome?

Strategy

I do not believe that I started with a well-defined strategy. At that time (I’m speaking about the 1980s and the beginning of the 1990s), I really wanted to start researching and transferring relevant data to practice: to teach future professionals based on scientific knowledge and to train real swimmers daily... and win, both as a teacher and as a coach. As a scientist, I had no real expectations about becoming a kind of a winner, so this text feels like a fantasy.

Although it was a long time ago, some basic concerns were already prominent in those starting years:

(i) Being almost alone, it was decisive to join together a team of ‘believers’ (both at the University and at the pool). To achieve this, it was mandatory to make evident that, to an ‘academic coach’ with a supposed solid theoretical background instead of a life of practice, it would be possible to reach high practical success. This required me to be genuine, coherent and persistent.

(ii) Having no research resources and equipment (nor habits and traditions), establishing synergies and partnerships with solid and recognised research groups (RG) should be a priority, both for empowering intervention capabilities—as for image management—and for obtaining financial support.

(iii) Exploring the most comprehensive and informational research problems, potentially the most relevant for practitioners, was paramount to potentiate the capacity of providing relevant assistance to the practical scene.

(iv) Progressively extending the experimental capabilities of the research group and empowering collaborative interdisciplinary approaches, was decisive for being able to ‘provide new answers to most of the old questions.’
Honing efforts on increasing the availability of emerging technologies to help coaches and swimmers to improve their performance was crucial for the recognition of swimmers, coaches, clubs, federations and national Olympic Committee (NOC) deciders. Persuasive abilities were required!

Figure 1 synthesises the main concerns previously discussed. From the above highlighted aspects, we will continue elaborating on those considered more relevant in the past, as well as possible ingredients for initiatives to come from possible readers.

**Figure 1**  Main domains and strategic concerns for the architecture of ‘building up’ in swimming science and practice

**Linking the Theory and Practice Worlds**

I believe in fundamental research, of course! However, it is well known the usual time gap in the production of outcomes, the development of meaningful applications, and the community recognition of the effective profits associated with the progression of fundamental knowledge. Indeed, the community recognition of the applied research, or even the so-called ‘semi-applied’ research, may be much easier and faster than fundamental research, also increasing the persuasive capacities close to the financing institutions. Thus, the strategy of enduring as a swimming coach while attempting to permanently apply the values of knowledge and research to daily practice seriously paid off. This was probably so because, concomitantly, some sport success was obtained, step by step. Indeed, after a period of exclusion from the sports community, and ‘negation’ of the scientist/coach profile (considered as a ‘theorist’ with everything to prove on practice), results started to appear, and the technical community became more and more complacent, until they accepted and valorised that particular profile. The ‘scientist-coach’ was then, in a period of seven seasons, a three-time ‘Portuguese Coach of the Year’, with six consecutive nominations by the peers. Indeed, this profile was followed, and other Ph.D. and M.Sc. coaches appeared at the Portuguese Swimming scene. At a given time, there has been more than six Ph.D., and more than 30 M.Sc. coaches involved in swimming.

This phenomena allowed an increased recognition of the academically educated coaches from the sports community and made easy the connections and cooperation among the universities, the swimming federation, regional associations, clubs, coaches and swimmers. Research projects
enrolling good swimmers were easily made possible since then. Furthermore, training control, evaluation and advice promoted by the university to serve national, regional, and club teams, became a reality.

**Exploring the Most Comprehensive and Informational Research Problems**

At the beginning of our research activity, we were impelled to follow the one we still consider the most promising pathway: to explore the biomechanics and physiology interactions that we first learned from Treffene et al. (1979) and, more powerfully, from di Prampero et al. (1974) and Pendergast et al. (1979). Indeed, we were convinced that the understanding of swimming performance relevant to training should rely on knowledge of the factors determining energy availability for the biologic work and on the recognition of the most appropriated biomechanical solutions to use for enhancing performance. Thus, we started exploring the concept of swimming economy, and related problems (Vilas-Boas 1990). In 1994, we used direct measurement of Oxygen consumption ($\text{VO}_2$) for the first time in non-flume-free swimming, and we were able to show that flat breaststroke, compared to the undulated one, may consume less energy to swim 200m close to race pace (Vilas-Boas 1993; Vilas-Boas & Santos 1994). Data from Vilas-Boas (1993) also showed interesting relationships between limb kinematics obtained by light-trace technology, energy cost and speed fluctuations. These findings were obtained at a time when undulated breaststroke (extreme undulate breaststroke) was internationally valorised, mostly from the strong influence of Leuven’s contributions (eg. Persyn et al. 1992). Moreover, our outcomes were based on strong individual relationships experimentally and originally observed between horizontal speed fluctuations and total energy cost in breaststroke swimming (Vilas-Boas 1996), exactly the same argument underpinning Leuven’s conclusions but in this case without energy cost estimations or measurements. Interestingly, despite those Portuguese contributions for a flat breaststroke biophysical superiority recognition, as opposed to the Belgian undulating one, the appearance of a world record holder like Deburghgraeve (BEL) was almost time coincident, swimming pretty flat the 100m event at the 1996 Atlanta Olympic Games. It’s curious to observe, nowadays, how many breaststrokers perform closer to Lempereur or Becue, and how many, on the contrary, perform closest to Deburghgraeve.

Years later we were able to follow the same approach for the alternated swimming techniques (Barbosa et al. 2006) and also for butterfly swimming (Barbosa et al. 2005a,b), concluding that intracyclic speed fluctuations were a major determinant factor of swimming energy cost. Moreover, it was possible to figure out that, in the butterfly stroke, speed fluctuations (Barbosa et al. 2008b) depended on limb kinematics, and that stroke mechanics determine energy cost (Barbosa et al. 2008a). As a consequence, we developed and tested a speedometer biofeedback system for training advice based on these findings (Lima et al. 2006). Nowadays, this cable system is about to be replaced by 3D inertial measurement units—IMUs (Vilas-Boas et al. 2011). In accordance, the possibility of mimicking the centre of mass (CM) kinematics through the use of a fixed body landmark (Barbosa et al. 2003; Figueiredo et al. 2009; Fernandes et al. 2012) has become a fundamental issue to sustain the use of speedsometers and IMUs for full-body kinematical approaches. The results, however, are still controversial, since it is not clear whether they are due to the in-body CM real mobility or to its estimation’s associated errors. The speedometer was also used for the assessment of a putative solution to mark the limits of the individual ATP/CP system in training, particularly through changes in the frequency spectra of the time variation of velocity (Soares et al. 2006). Evaluation of the anaerobic performance potential was also attempted using tethered swimming in the different techniques, but with a more classical approach using the fatigue index (Morouço et al. 2011). Indeed, marking the limits of the anaerobic pathways has also been a long-central issue of our group. In 1991, at the FINA medical conference held in Brazil, we explored, in this sense, the kinetics of the Blood Lactate Increasing Speed (BLIS) concept during a 100m freestyle event (Vilas-Boas & Duarte 1991).

Despite holding onto the same main research question from the 1980s until today (how biomechanics and physiology combine in performance), time has led us to extend our curiosity to the effects of gender (Fernandes et al. 2005), and coordination (Fernandes et al. 2010) on energy cost.
Progressively, new methodologies and instrumentations were included, allowing us to explore new exercise intensities, exertion conditions, and research questions. New availabilities included: (i) breath by breath VO\(_2\) assessment, VO\(_2\) and blood [La\(^-\)] kinetics, as well as total energy consumption and energy partition kinetics (Figueiredo et al. 2011, 2013d; Sousa et al. 2011, 2013), (ii) limbs and whole body 2D and 3D kinematics, both through video (Barbosa et al. 1999; de Jesus et al. 2012a,b; Figueiredo et al. 2013c) and real time MoCap techniques (Ribeiro et al. 2014, this volume), also extended to coordination (Soares et al. 1999; Fernandes et al. 2010; Querido et al. 2010; Figueiredo et al. 2012) and indirect efficiency analysis (Figueiredo et al. 2011, 2013d), (iii) tethered propulsion (Morouço et al. 2011), passive (Vilas-Boas et al. 2010a) and active drag assessment (Kolmogorov et al. 2000; Vilas-Boas et al. 2001; Ribeiro et al. 2013), (iv) EMG profiles (amplitude, timing and frequency analysis) both for segment-animation analysis (Oliveira et al. 2010; Figueiredo et al. 2013c), and joint stabilisation and stiffness modulation (Lauer et al. 2014), as well as for fatigue analysis (Figueiredo et al. 2013c), and (v) more recently, thermography (de Jesus et al. 2012c). The two late approaches are intended to ‘open a window’ to the internal biomechanics.

Figure 2 shows the holistic approach to the swimming science of our group, based on the simple idea that a given and limited amount of energy should be maximally explored during a distance-based event, allowing no minimise the competition time duration.

This holistic approach was applied to different types of swimmers (young, university level, elite, handicapped, synchronised, water-polo players, and life-saving swimmers), different swimming techniques and variants, as well as to other water-movement modes. Virtual swimming studies were also already conducted (Soltany et al. 2013). Turns (Pereira et al. 2007, 2008; Araújo et al. 2010), and particularly starts (Vilas-Boas et al. 2003; Ventorre et al. 2010; de Jesus et al. 2011, 2013) had also become very relevant topics of interest, closing the circle of the swimmers’ most relevant actions. For these studies, specific dynamometric solutions were used and developed. In parallel, both experimental and numerical (Computational Fluid Dynamics—CFD) approaches were used for the evaluation of materials like line-separation ropes (Vilas-Boas et al. 2010b) and equipment like swimsuits and caps (Marinho et al. 2011, 2012). CFD was also explored to allow further insight into
propulsion (Marinho et al. 2010) and drag (Silva et al. 2008), and for reciprocally analysing the accuracy of numerical and inverse dynamics’ experimental and analytical approaches (Costa et al. 2011).

A question should be raised here as to whether or not it’s wise for a research group to spread its attention for so diverse a field of interests. Wouldn’t it be preferable to focus on a real and narrow expertise domain? For specialisation purposes, the second solution is, for sure, much more suitable, but human curiosity and, particularly, the capabilities of the research centre to intervene into practice, has determined the holistic strategy followed. Moreover, it seems to empower the attraction capacity for national and international academic, scientific, sportive, technological and industrial partnerships.

Diversity also gave origin to the University of Porto Biomechanics Laboratory (LABIOMEP), gathering the faculties of Medicine, Veterinarian, Dentistry, Sciences, Engineering and Sport. In fact, this new research centre – and its ‘aquatic section’, the LABIOMEP H2O – was built in accordance with a strategy of competencies’ integration, promoting the interaction of different areas of expertise, which allowed the inclusion of new concepts, methods, and instruments. This is proving to be a winning strategy, mostly due to the empowerment of the critical mass behind each problem to be addressed, but also because it allowed different equipment to be available or developed in a dedicated perspective. Compared to an isolated situation, I can say that we are presently at the ‘cutting edge of modernity’. Furthermore, the capacity of the research group to interact and negotiate collaborations with stable companies is clearly improved. In our case, it’s possible to underline the examples of the partnerships with Cosmed (Ita), for the development and validation of the Aquatrainer II snorkel for bxb oximetry in swimming (Baldari et al. 2013); with Qualisys (Swe), for the dual media MoCap development; with different brands of competition swimsuits for product development and also the expected partnership with a well-known company for underwater EMG technology development.

**Strengthening National and International Scientific Cooperation and Synergies**

For a peripheral country with marginal competitive swimming, the fulfilment of the aim and vision of the research group was only possible through a broad number of synergies with other research groups, technological centres, swimming teams, research material companies and equipment development and manufacturing companies. Among us, this task was assumed to be a nuclear one, like everything in life, the proper connections were decisive to allow for the fulfilment of the purposes of the research group. If our team was able to accomplish something in the past, something that might be relevant both for science and for sport, that was for sure a fruitful outcome of one or more partnerships. Collaborations shouldn’t be monogamist; they should, instead, be diverse, empowering the required plurality of perspectives and contributions – a true critical-mass increase! Thus, regarding this fundamental vector of growing, my message for the future is rather clear: Try, as hard as possible, to develop and strengthen collaborative partnerships within the swimming science family, enabling coping capabilities for the challenges to come through the merging of different competencies.

In our case, beyond the Portuguese partners and after the seminal collaboration with Persyn’s research group, further collaboration with Leuven was possible through Daly; nuclear collaborative work was done with Billat, Keskinen and Rodriguez, particularly exploring the bxb VO2 assessment technologies that were recently upgraded with the Rome’s group (Baldari and Guidetti) and the new Cosmed snorkel validation. Extending our interests to the coordination domain was possible through the Rouen’s group, with the contributions of Chollet, Seifert and Vantorre. Dry land and underwater dynamometry enrolled the Roesler group for turns and starts. Body roll and swimming kinematic synergies were established with Sanders and Castro & Guimarães (Castro et al. 2006). Efficiency, propulsion and drag effects were considered with Zamparo, Kjendlie, Kolmogorov and Toussaint. EMG partnerships were consolidated with Rouard, and a relative-weight analysis of the factors involved in swimming speed has been conducted with Pendergast (Figueiredo et al. 2013a), showing that swimming performance is a multifactorial determined phenomena.
**Conclusion**

From the previous ‘building up’ story, it is possible to extract a number of clues that I think relevant to similar initiatives trying to fulfil the aims of the World Commission of Sciences and Sports: (i) a peripheral country with also a peripheral swimming sport may and should aim to build an ambitious research group, (ii) explicit, coherent and consistent relationships with practice are paramount for the development of the group, (iii) scientifically exploring a number of relevant parameters for the understanding of swimming performance and coaching may be more preferable than restricting oneself to a few specialities, (iv) making available a number of methods, instruments and tools that allow for the evaluation and advice of swimmers and coaches in non-trivial domains may be a wise strategy, (v) empowering national and international synergies is crucial for enlarging critical-mass, reducing weaknesses, and increasing credibility and persuasive ability.

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**References**


Injury to swimmers: bad luck, bad athletes or bad management

Peter Blanch

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Abstract

Due to the high repetitious workload of swimming training, overuse injuries especially of the shoulder are a costly problem for swimming. Due to different logistical reasons long term injury surveillance in swimming has not been achieved and research is often around perceived risk factors examined retrospectively and/or cross-sectionally. The identified risk factors often place ‘the blame’ for injury on some sort of athlete inadequacy (genetic, flexibility, strength, technique). However the most consistent findings that occur in the literature related to injury are to do with training volume and structure. Training ramped up too quickly, taken too high or maintained at monotonous levels are all related to injury. This of course places considerable responsibility on the coach. The basic recording of injury history and injury costs associated with measurement of the load athletes are placed under is fundamental information required for swimming to advance in the area of injury prevention.
Injury to an athlete is a frustrating time for all involved. In swimming with its high repetitive workload, overuse injuries to especially the shoulder can interfere with training and competition and in some cases be career ending. The path for good injury prevention strategies in sport was outlined by van Mechelen et al. over 20 years ago (van Mechelen, Hlobil & Kemper 1992). They outlined a simple four step procedure:

1. **Measure your costs** - Have an injury surveillance system in place so the type and severity of injuries can be ascertained.
2. **Determine risk factors** - Take measures and examine their relationship to the injury rates.
3. **Intervene** - After you have identified your risk factors develop programs to address those identified risk factors.
4. **Re-assess** - Use your injury surveillance system to ascertain whether changes have been made to injury rates.

Swimming has never been able to quite to close this loop although the work done in the USA collegiate system is beginning to show this level of sophistication (Chase, Caine, Goodwin, Whitehead & Romanick 2013; Harrington, Meisel & Tate 2014). While individual clubs and/or universities swimming programs have been involved in research, the long term injury surveillance that has been achieved in other sports is not in place for swimming (J. Orchard, James, Alcott, Carter & Farhart 2002; J. Orchard & Seward 2002; J.W. Orchard, James & Portus 2006; J.W. Orchard, Seward & Orchard 2013).

So while not being quite able to have Step 1 of the van Mechelen protocol in place a lot of effort has been placed on step 2, trying to identify risk factors. These studies tend to be retrospective or cross-sectional in nature. Interestingly, a lot of the risk factors hypothesised to why injuries occur revolve around some inadequacy of the athlete. These relate to range of motion, strength, muscle patterning and technique. The evidence for these risk factors is generally weak.

While research has not been done specifically on swimmers there is growing evidence that genetics has a strong role to play in injury. Collins et al. (Collins & Raleigh 2009) have clearly defined different genetic sequence variations that predispose subjects to different soft tissue pathologies. Further work on military recruits by Korvala et al. (Korvala et al. 2010) showed that when a soldier had a combination of identified allele’s associated with bone turnover that were at a 3 times higher risk of stress fracture. This evidence can be perceived again to place the responsibility of injury on the athlete however what it should reinforce is the need for an individualisation approach due to genetic factors.

One risk factor that continually is identified in swimming (and other sports) which is perhaps more an inadequacy of the coach is training volume and structure (Gaunt & Maffulli 2012; Sein et al. 2010; Tate et al. 2012). The very definition of an overuse injury is that the load placed upon a structure is greater than its ability to adapt to that load, so any time an athlete suffers an overuse injury it should be considered a loading mistake. The converse of this is of course a structure’s ability to absorb load is related to it’s loading history. The fine line between training hard and long enough to produce an individual’s best performance but not so hard as to tip over the edge to injury is a challenge not only for swimming but all sports.

Often in discussions on training there is perhaps an unspoken belief that the relationship between training load and performance is linear i.e. the more an athlete trains the better they will perform. This belief is often fuelled by a case history of an extraordinary athlete, performing very well who has completed extraordinary training volume. This athlete can easily become the ‘benchmark’ and athletes that don’t measure up are either ‘too weak’ or ‘are not going to make it anyway’. These unsustainable beliefs driving an ‘eggs against the wall’ mentality has possibly led to far more injuries.
than anything else. It is possible to exceed all athletes ability to respond by ramping too quickly (Hulin et al. 2013), exceeding a ceiling (J.W. Orchard, James, Portus, Kountouris & Dennis 2009) or maintaining a monotonous load (Anderson, Tripplett-McBride, Foster, Doberstein & Brice 2003). Unless consistent measurements and modelling of the loads are kept and reviewed which is difficult, it is far easier to ‘lay the blame’ on the athlete.

While there is no doubt that there are individual attributes of an athlete that puts them at higher risk of injury no swimmer gets swimmer’s shoulder unless they swim a lot. Injuries are always about the load, variable risk factors such as training history, age, technique, flexibility, strength, injury history and genetics then only modulate the load for that individual.

References


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Computational fluid dynamics as a tool for improving stroke technique

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Abstract

Human swimming is a highly competitive sport where performance has a complex dependence on technique, fluid dynamics, biomechanics, and physiology. Computational fluid dynamics (CFD) is increasingly being used as a tool to study elite level human swimming. This approach complements traditional pool based experimentation, providing previously unobtainable data to provide new insights into the relationships between stroke technique and performance. In this paper, pool based experimentation is reviewed along with recent developments in the field of swimming CFD. Finally, the future directions of the field of swimming CFD are proposed which will see it become an indispensable tool for elite athletes seeking improved stroke technique.

Introduction

In all thirty-four swimming events at the 2012 London Olympics the Silver medallist finished within 1.74\% of the time of the Gold medallist ('London 2012 Summer Olympics' 2014). Half of these events had gold-silver finishing times which were within 0.73\% of each other. This highlights that winning and losing at the elite level comes down to very small fractions of swimmer speed. In this competitive environment, swimmers and their coaches continuously strive to get an edge over their rivals. Together they work towards optimising swimming performance by maximising thrust and minimising drag. However these objectives result from a complex interplay between fluid dynamics, swimmer biomechanics and physiology. Improving understanding of the swimmer’s fluid dynamics and the relationship between technique and performance is a key aspect of swimming and are the focus of this review paper. Specifically the benefits of experimental swimming research are explored, along with the emerging field of CFD for swimming research. This provides context for the final recommendations for the future directions of CFD for swimming.

Experimental swimming research

Relating kinematics and performance

The performance of swimmers is judged solely by the time on the finishing clock at the end of a race. In isolation this performance measure says little about the underlying relationships between technique, fluid dynamics and biomechanics. A number of performance measures are observable during free swimming which have been investigated experimentally in the literature.

The speed of the swimmer ($v$) may be expressed as the product of the stroke rate (SR) and the stroke length (SL) (Craig & Pendeegast 1979; Craig et al. 1985),

$$v = \text{SR} \times SL.$$ 

This implies that to move fast the swimmer must try to go as far as possible during each stroke by maintaining good technique and body positioning whilst also trying to keep as high a stroke rate as possible (Wei, Mark & Hutchison 2014). Craig et al. (1985) studied elite swimmers in competition to determine the relationships between $v$, SR and SL. A larger SL was observed to be related to better performance across athletes. The reduction in swimmer speed throughout a race is associated with a decrease in SL (for all strokes) for which swimmers seek to compensate by increasing their SR. The reduction in SL with fatigue is caused by the swimmer’s body positioning becoming less streamlined leading to increased drag and a reduced gliding distance during the strokes.
The stroke index (SI) performance measure is given by the product

$$SI = SR \times v.$$  

Costill et al. (1985) studied SI using swimming experiments which also measured swimmer energy expenditure (C) from athlete oxygen consumption. They found that high SI was associated with low C and was therefore a useful performance measure. Barbosa et al. (2010) discussed that C and SI are both dependent on v which confuses the interpretation of SI values and its physical meaning.

Another performance measure is the intra-cyclic variation of the swimmer centre of mass speed (dV) which is given by

$$dV = \sqrt{\frac{\sum (v_i - v)^2 F_i / n}{\sum v_i F_i / n}}  \times \frac{100}{n}$$

Barbosa et al. (2005) studied dV in butterfly swimming where they also calculated total energy expenditure from earlobe blood samples and oxygen consumption measurements. They found that energy cost is significantly associated with dV. More recently Barbosa et al. (2010) found that freestyle and backstroke had smaller dV values than butterfly and breaststroke, implying that freestyle and backstroke require less energy expenditure per stroke. At this time dV is not a universally accepted performance measure because there are conflicting reports of the relationship between dV and v in the literature (Barbosa et al. 2010).

Inter-limb coordination (Chollet, Chalies & Chatard 2000) is another kinematic measure that changes with swimming speed and performance. The index of coordination (IdC) is defined as the time gap between propulsive phases of the arms in the alternated strokes (freestyle and backstroke) whilst the total time gap (TTG) is the time gap between propulsive phases of the arms and legs in the synchronised limb strokes (butterfly and breaststroke). In higher speed swimming the IdC tends to be positive and the swimmer has overlapping periods of propulsion called superposition, whereas in lower speed swimming the IdC becomes negative and the arms are in a ‘catch up’ technique regime.

All these performance metrics are easy to measure so have been part of large statistical studies across many athletes ranging between gender, age, ability and by physical attributes. Unfortunately they tend to say little about the underlying physical mechanisms that cause the performance changes in the athletes, making informed choices about stroke optimisation difficult.

**Force measurement experiments**

To gain more insights into swimming forces, a number of studies have sought to measure forces directly produced by the swimmer. The first attempt was the Measure Active Drag (MAD) system (Toussaint et al. 1988 1990) in which a freestyle swimmer (propelling using their arms only) would push off fixed pads with their hands during their underwater arm strokes. Each pad would measure the thrust produced by the swimmer which is equivalent to the active drag of the swimmer who is moving at a constant speed. By simultaneously measuring the oxygen consumption, the energy expenditure could be calculated and the mechanical efficiency of the athletes could be determined.

The Velocity Perturbation Approach (VPM) is another method for determining the active drag of swimmers (Kolmogorov & Duplishcheva 1992; Kolmogorov et al. 1997). In this approach an athlete swims two trials at maximal intensity, one as a free swimmer and the other whilst towing a hydrodynamic buoy that provides an additional known drag force. Under the assumption of equal power being generated by the swimmer during both trials, the active drag of the swimmer can be calculated from these experiments. Other researchers use apparatus which tows the swimmer at
higher speed than free swimming whilst measuring the tension in the cable (Alcock & Mason 2007). In a similar manner the active drag can be calculated from these experiments.

Toussaint, Roos & Kolmogorov (2004) compared the MAD-system and the VPM method. They claimed that the active drag provided by both methods was significantly different and suggested that the difference could be explained by a violation of the equal power assumption in their VPM experiments.

An apparatus for measuring kicking forces has also been used consisting of a steel frame force balance that the swimmer holds on to with their hands whilst kicking (Legac et al. 2008; Wei, Mark & Hutchison 2014). This enabled time-resolved leg forces to be measured which can be related to the technique. The common downside of all these force measuring approaches is that they impact on the stroke technique employed by the athlete during free swimming.

A less invasive method of determining the swimmer forces is to track the swimmer position from video footage and to determine the acceleration from the second derivative of position (Legac et al. 2008; Wei, Mark & Hutchison 2014). This provides useful information about the athlete during free swimming but there is no way to decompose the net forces down further into thrust and drag or by contributions from individual limbs.

**Flow visualisation**

A small number of studies have sought to visualise the flowfields around swimmers using digital particle image velocimetry (DPIV) (Legac et al. 2008; Hochstein & Blickhan 2011). By shining a sheet of sunlight through water seeded by small bubbles, the in-plane velocity field can be determined from the video footage. From this data critical vortex structures for propulsion have been identified for dolphin kick (Hochstein & Blickhan 2011). It has even been used to inform breaststroke technique modification for an athlete (Wei, Mark & Hutchison 2014). This method provides measured quantitative details of the flow field. Unfortunately this approach only provides data on a single plane and multiple small windows of velocity field must be composited together to show the flow field around the whole swimmer.

**Computational fluid dynamics research**

CFD is a mature technology in many engineering fields including the aviation and automotive industries. It has only recently begun to be applied to human swimming. The is partly due to swimming’s unique combination of difficult modelling challenges including a high Reynolds number turbulent flow field with transition along the body; a fluid free surface with bubbles, entrained gas and splashing; and the rapidly deforming body of the swimmer. In this section the progression of CFD towards modelling full body swimming is reviewed. CFD offers new opportunities for non-invasive experimentation with stroke technique in a controllable, repeatable testing environment. It can also provide significant amounts of data that is unobtainable from pool based experimentation, enabling the underlying physical mechanisms to be understood.

**Hand and Arm Flow Simulations**

Bixler & Schloder (1996) pioneered swimming CFD with studies of flow around a circular disk having the same areas as the swimmer’s hand. They found that hand acceleration is important to the propulsive forces that are generated and that the added mass concept is important to understand for generating propulsion from the underwater arm stroke. Later Bixler & Riewald (2002) used the Fluent (ANSYS, Pennsylvania, USA) finite volume solver to model flow over a realistic hand and arm geometry and compared the results with wind tunnel experiments. Their steady state force coefficients compared well with experimental values and they were able to determine hand angles for maximum drag and lift. Subsequently Gardano & Dabnichki (2006) used Fluent to simulate flow over an entire human arm and measured the lift and drag in multiple fixed positions across the entire stroke range.
**Streamline Passive Glide**

Bixler, Pease & Fairhurst (2007) used Fluent to study the flow over a full swimmer model in a streamline passive glide pose and compared the drag forces to those obtained from flume experiments of both a swimmer and mannequin. In the process they established the accuracy of Fluent for modelling submerged streamline glide. Marinho et al. (2009) used Fluent to study different body positions during passive glide, demonstrating a process of stroke optimisation using CFD. More recently Novais et al. (2012) used Fluent to study the effect of depth on drag during streamline glide and were able determine the optimal depth for gliding during starts and turns.

**Submerged Dolphin Kick Swimming**

Early dolphin kick studies were conducted by Lyttle & Keys (2006) using Fluent to investigate large amplitude slow kicking against small amplitude fast kicking. They determined the critical speed above which small amplitude kicking should be used and below which the large amplitude kicking is optimal.

Another group investigated dolphin kick swimming in detail using an immersed boundary flow solver (von Loebbecke, Mittal, Fish, et al. 2009; von Loebbecke, Mittal, Mark, et al. 2009). They were able to determine that most of the thrust is generated by the swimmer’s feet and that a three-dimensional vortex ring is created during the stroke which is associated with the propulsion. They also quantified the difference in thrust between the upstrokes and downstrokes of the kicking legs. Energetics was also considered in this study with the quantification of mechanical efficiency of the stroke, being defined as the useful work divided by the total work.

More recently Cohen, Cleary & Mason (2012) studied submerged dolphin kick swimming using the smoothed particle hydrodynamics (SPH) grid-less method which is well suited to such problems with deforming boundaries. They investigated the performance impacts of changes in both ankle flexibility and stroke rate. The results suggested that net streamwise force on the swimmer is relatively insensitive to ankle flexibility but is strongly dependent on kick frequency. Thrust generation was also shown to be stronger in the extension kick than the flexion kick, both in the measured forces and in the strength of the associated vortex ring flow structures.

Hochstein et al. (2012) used the OpenFOAM (The OpenFOAM Team, www.openfoam.org) finite volume solver to model dolphin kick swimming in a study to investigate whether vortices generated higher on the body can be recaptured by the legs which would enhance propulsion. This highlighted the complex nature of the fluid dynamics that is responsible for the swimmer’s motion.

**Freestyle swimming**

Freestyle swimming on a free surface is challenging problem to simulate and there have only been a small number of studies that have tackled this to date. Nakashima, Satou & Miura (2007) developed a quasi-CFD method (which doesn’t solve the Navier-Stokes equations) for simulating human swimming. Their approach used a segmented human model whose segment forces were calculated from experimentally determined force coefficients. By prescribing freestyle kinematics onto their model they were able to make it swim dynamically through water. Subsequently Nakashima & Motegi (2007) coupled model to a full body musculo-skeletal simulator for swimming, enabling muscle activity to be quantified.

Von Loebbecke & Mittal (2012) used an immersed boundary method to study an isolated whole arm performing distinct underwater arm stroke styles. They found that large lateral sculling motions reduce both lift and drag forces on the arm and are detrimental to performance. Debate has existed on this topic since the 1970s (Wei, Mark & Hutchison 2014) so this study is finally helping to settle this matter.

Cleary et al. (2013) used the SPH approach to model full-body freestyle swimming on a free surface. A realistic swimmer geometry was obtained from a laser body scan and multi-angle video footage was taken of the stroke. A manual kinematics digitisation process was undertaken to create a
biomechanical model of the swimming athlete. This was then placed into the virtual pool and allowed to swim dynamically. Swimmer forces and flowfields were obtained, allowing individual limb thrust contributions to be quantified and the vortical structures generated to be visualised. The authors have also applied the SPH method to model swimming of the other three swimming strokes — backstroke, butterfly and breaststroke. Harrison, Cohen & Cleary (2014) extended this modelling to include internal biomechanical joint structures, so that joint torques and powers could be calculated, providing details of the swimmer exertion for analysis.

**Recommendations for future swimming CFD directions**

In this paper the progression of swimming research has been reviewed. Swimming CFD has moved from infancy to a promising tool which can be used to provide practical knowledge to swimming practitioners. For swimming CFD to advance further in the future a number of developments are needed including:

- Improved motion capture systems which easily and efficiently record swimmer kinematics and generate swimming biomechanical models. This will enable large statistical studies to be undertaken across many cycles of an individual athlete and across many athletes.

- Purpose built software for reduced turn-around times of studies to quickly provide recommendations for athletes and coaches who work towards short term competition deadlines.

- Automated ability to explore larger parameter spaces of stroke technique variants during computational optimisation studies.

- Improved swimmer models which include individualised constraints on flexibility and strength. Biomechanical models should also include full muscle models so swimmer energetics can be quantified.

- Improved fluid dynamics modelling capabilities to capture the fine scales of the turbulence; flow transition; skin and swimsuit deformation; and bubbles.

With CFD in the arsenal of the twenty-first century swimming sports scientist, a greater level of understanding of technique, performance and fluid dynamics awaits.

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Limitations on swimming speed: how can natural technologies be utilised?

Frank E Fish

Abstract

Despite improvements in training, technique and conditioning, human swimming performance is limited in terms of speed due to the constraints of biology and physics. In comparison, animals greatly exceed human swimming performance. Examination of the morphology, mechanics and hydrodynamics of animal swimming can provide insights into mechanisms to efficiently reduce swimming effort and avoid constraints on speed. Animals are capable of manipulating flow around the body both passively and actively. Passive mechanisms rely on structural and morphological components of the body. Streamlined, fusiform body designs are ubiquitous in fast-swimming animals to minimise drag. The texture and composition of the skin surface further minimises drag by a reduction in water friction and delay of separation effects. The skin of marine animals is tighter than the integument of humans. The pliability of human skin produces mobile skin folds that add to drag. A particularly limitation to human performance is swimming in close proximity to the water surface. This position generates waves that increase drag. In addition, interference within the wave pattern traps the swimmer within a trough that produces a barrier to maximum speed. Active mechanisms by animals for enhanced propulsion utilise vorticity control for thrust production. Fast-swimming animals move their appendages in an oscillatory manner in which wing-like blades produce lift as the primary propulsive force. Humans swim with a paddling, drag-based mechanism. Although effective for propulsion, drag-based swimming is limited to use at low speeds and has reduced efficiency, whereas lift-based mechanisms operate at high speeds with high propulsive efficiency. The thrust is produced in association with the momentum shed by the swimmer into the water. The manifestation of this shed momentum is the wake, which is composed of a thrust producing jet and alternating pairs of vortices. The pattern of vortices for humans indicate severe limits to the fastest speed that can be attained. Compared to human swimmers, aquatic animals have an advantage of being adapted to life in water that permits greater swimming performance than for humans.

Introduction

Among all the primates, humans have had the greatest association with water. Indeed, humans are amazingly at home in the water. Even newborns can hold their breath and demonstrate rudimentary swimming behavior. The ability of humans to swim is recorded from antiquity. In more modern times, human swimming has become a competitive sport. Times and speeds have been recorded that have shown a steady improvement of the performance of competitive swimmers. Since the late 1800s to present, records indicate a steady reduction in times over a measured distance with a concomitant increase in speed (Fig. 1). This faster performance is due to improvements in training, technique, conditioning and technology. However, human swimming performance is rapidly approaching an asymptote (Fig. 1) to swim varied distances for both long and short courses. Today, new speed records are measured in fractions of a second. There appears to be a limit in how fast humans can swim.

Various aquatic animals travel at speeds far in excess of human swimming performance. Swordfish (Xiphias gladius) and marlin (Makaira indica) have the highest maximum speeds of 36 m/s (70 kts) (Aleyev 1977). Whales and dolphins can travel at speeds up to 11.3-17.5 m/s (22-34 kts) (Fish & Rohr
These fish and marine mammals power their streamlined bodies through the water by oscillation of broad wing-like propulsors (e.g., caudal fin, flukes). Furthermore, the undulatory motions of salmon can generate high accelerations for leaps to negotiate obstacles and waterfalls during upstream migrations (Lauritzen et al. 2005). The ability of animals to move at such high speeds is a function of adaptations that have evolved over millions of years. In an environment that is 800 times denser and 60 times more viscous than air, drag is a major hindrance to high-speed locomotion that must be offset by enhanced thrust capabilities. For fast swimming aquatic animals, Natural Selection is the crucible by which their performance is judged and their adaptations honed. Life or death ultimately determines if an animal has been successful rather than the awarding of medals in competitive swimming. Under such unforgiving selection, the pressure to push the performance envelope of speed has required modifications to the morphology, physiology and behavior of swimming animals.

Both human and animal swimmers are constrained by the same physical forces from the hydrodynamics of the aquatic medium. However aquatic animals demonstrate greater adaptation for high-speed swimming than humans. Thus, examination of the morphology, mechanics and hydrodynamics of animal swimming may provide insights into mechanisms to avoid constraints on speed and efficiently reduce swimming effort.

**Hydrodynamics of swimming in animals**

**Minimising drag**

Propulsion in water is the result of the transfer of momentum from the animal to the aquatic medium, whereas the momentum transferred from the water to the animal is responsible for resistive forces (Webb 1988). The primary resistive hydrodynamic force for steady swimming by animals is drag. The components of drag vary in accordance with (1) flow conditions around the animal, (2) proximity to the water surface (air-water interface), and (3) the relative predominance of inertial, viscous, and gravitational forces. Flow conditions and drag forces are determined by the size and speed of the animal in conjunction with density and viscosity.

When swimming submerged, frictional and pressure components of drag dominate (Webb 1975; Vogel 1994). Frictional drag originates from fluid viscosity, which produces shear stresses in the boundary layer (a layer of water extending out from the body to the point at which it is moving at 99% of free stream speed (Webb 1975)). The magnitude of frictional drag will depend on the wetted surface area of the body and flow conditions (laminar, turbulent, or transitional) within the boundary layer (Webb 1975). For large aquatic mammals operating at high swimming speed, transition from...
laminar to turbulent flow conditions can occur (Gray 1936; Fish & Hui 1991), which includes humans. A boundary layer with turbulent flow produces a higher frictional drag than laminar flow (Webb 1975).

Pressure drag arises from pressure differences in the flow outside of the boundary layer due to distortion of the flow around the body. Deflection of this outer flow due to body shape produces pressure gradients from varying flow velocities. The pressure differential from leading to trailing edges of the body is the source of the drag (Webb 1975; Vogel 1994). Streamlining minimises drag by reducing the magnitude of the pressure gradient over the body. Increased pressure drag can occur due to interaction of the boundary layer and adverse pressure gradients resulting in separation of the boundary layer from the body. Interaction of the boundary layer and the outer flow produces a net pressure force that acts in opposition to forward motion, as kinetic energy is lost in the wake. Drag is minimised when separation is avoided.

Drag is minimised primarily by streamlining the shape of the body and the appendages to reduce pressure drag. In this regard, humans are at a major disadvantage compared to aquatic animals. Animals, such as fish and marine mammals, have streamlined profiles that are characterised by fusiform shapes emulating an elongate teardrop with a rounded leading edge extending to a maximum thickness and a slowly tapering tail. The fusiform shape is also found in the profile of the appendages (e.g. fins, flukes, flippers) (Fish 2004; Fish et al. 2007). Streamlining minimises drag by reducing the magnitude of the pressure gradient over the body and allows water to flow over the surface without separation (Vogel 1994). Humans do not show high streamlining and deviate considerably for the fusiform shape as the globular head is separated by a narrow neck from the rest of the body with broad shoulders and hips. The mobile legs and arms are long compared to the limbs of aquatic animals. In addition, drag is augmented by the protruding ear pinnae in humans. The ear pinnae of aquatic mammals are reduced or absent. The body shape of humans incurs substantial drag that can be two orders of magnitude greater than for fish and marine mammals (Webb 1975, Clary 1979; Aleyev 1977; Fish & Rohr 1999; Novais et al. 2012).

The naked skin and subcutaneous adipose tissue of humans has been hypothesised to be an adaptation for reduced drag in water similar to the skin of dolphins. Both skins have an elastic property, although the dolphin skin is less compliant than for humans. This compliance results in the formation of mobile skin folds at high speed (Essapian 1955; Aleyev 1977). Hydrodynamically generated folds move in a wavelike manner perpendicular to direction of movement in an anterior to posterior direction (Essapian 1955). It was hypothesised that the folds were a mechanism to dampen turbulence, but tests on naked women who were towed through water at speeds of 2-4 m/s (Aleyev 1977) indicated that the folds developed passively from the interaction of the dynamic water pressure and skin elasticity. The speed of the posterior movement of the folds was 10% lower than the towing speed. The folds were shown to increase the drag on the body. For dolphins, skin folds are minimised by the crossed helically wound layer of collagen fibers within and underlying the blubber (Pabst 1996, 2000). The analogue for humans would be modern full-body swimsuit that would suppress skin folds. Aleyev (1977) showed that when female subjects were tested while wearing a swimsuit to suppress the formation of skin folds, the drag was decreased 6.1% compared to nude women (Aleyev 1977).

Perhaps the greatest limitation to speed for humans occurs when swimming at or near the water surface. Along with frictional and pressure components of drag, proximity to the water surface incurs additional resistance from gravitational forces in production of surface waves (Vennell et al. 2006; Novais et al. 2012; Wei et al. 2014). Kinetic energy from the animal motion is lost as it is changed into potential energy in the formation of waves (Vogel 1994). This wave drag can reach a maximum of five times frictional drag (Hertel 1966). Maximum wave drag occurs when the body is just submerged at a relative depth of 0.5 of maximum body diameter (Hoerner 1965; Hertel 1966). Wave drag is negated with increasing or decreasing submergence depths, so that wave drag becomes unimportant at depths greater than 2-3 times body diameter or when the animal becomes airborne (Lang & Daybell 1963; Hertel 1966).
As opposed to submerged swimming with an exponential rise in drag with increasing velocity, the relationship between drag and velocity for surface swimming is more complex. While moving at the water surface, the body of an animal will act like a displacement hull of a ship producing two distinct systems of waves; bow wave system and stern wave system (Hoerner 1965). These systems are composed of diverging and transverse waves that each contributes half of the wave drag (Hoerner 1965). The diverging waves from bow and stern cannot interfere with one another; however, the transverse bow waves can be superimposed on the transverse stern waves because wavelength is variable with respect to speed (Marchaj 1964; Hoerner 1965). With increasing speed, the wavelength of the bow wave system increases and interferes with the waves generated at the stern (Marchaj 1964). Depending on the phase relationship, the bow and stern waves can produce a positive or negative interference. Thus, the drag on a body can be exaggerated when wave crests are synchronised and can be reduced when a wave crest and trough destructively interfere. As a result, for a body moving at the surface, the drag as a function of velocity shows ‘humps’ and ‘hollows’ (Lang & Daybell 1963; Hoerner 1965).

Speed at the water surface is constrained by the formation of surface waves (Prange & Schmidt-Nielsen 1970; Aigeldinger & Fish 1995). When the wavelength of the bow wave is equal to waterline length of the body, this effectively traps the animal in the trough of the bow wave, ultimately limiting further increases in speed (Vogel 1994). To move faster, an animal would have to swim over or through the bow wave, which are both energetically very costly. This effective speed limit for a conventional displacement hull, such as a ship or surface swimming animals, is called the hull speed (Prange & Schmidt-Nielsen 1970). Surface swimming animals rarely exceed hull speed (Williams 1989; Fish & Baudinette 1999) and are capable of greater speeds by submerged swimming (Williams 1989; Fish et al. 1997), porpoising (Au & Weihs 1980), and hydroplaning (Aigeldinger & Fish 1995). Only submerged swimming is available as an option for increased speed for humans.

**Maximising thrust**
Thrust is the reaction force to drag for an animal swimming at a constant velocity. Thrust is generated by actively transferring momentum from the moving parts of the body (i.e., propulsors) to the water. The rate of momentum exchange between the propulsor and the water determines the amount of thrust generated. The propulsors most efficiently maximise thrust by accelerating a large mass of fluid, but at a low velocity (Alexander 1983). Propulsors, therefore, are large in span and area (Webb 1988). Hence an increased volume of water is accelerated during the excursion of the propulsor. Thrust can be produced by moving appendages (e.g. arms and legs, fins, flippers, flukes) backward and forward along the axis of progression with the surface broadside to the flow, or up and down in a plane perpendicular to progression (Vogel 1994). The former constitutes a drag-based thrust, which is used by paddling animals (e.g., beaver, platypus), and the latter is a lift-based thrust from an oscillating wing-like structure (e.g. dolphin flukes, sea lion pectoral flippers). Drag-based propulsion allows for rapid acceleration but can only generate thrust at low speeds; whereas, lift-based propulsion can function at high speeds, but is limited at low speeds when there is insufficient flow over the propulsor surface to generate thrust (Fig. 2). Lift-based swimming is more efficient than drag-based swimming in that typical lift-based swimming generates thrust nearly continuously throughout the stroke, whereas drag-based swimming divides the stroke into a propulsive power phase and a resistive recovery phase (Webb 1975: Fish 1996).

The strokes used by humans for swimming depend on a drag-based mechanism to generate thrust. Despite assertions that lift is a significant component of the thrust in human swimming, the basic motion of the arm and hand are dominated by drag (Berger et al. 1995; von Loebbecke & Mittal 2012; Wei et al. 2013). Although in the freestyle, butterfly and backstroke there is no resistive drag produced in the recovery phase as the arms are removed from the water, the stroke is inefficient as thrust is generated only in the power phase, which is less than 50% of the stroke cycle (Chatard et al. 1990). The inability for any limb to continuously generate thrust means that drag-based swimming has a low propulsive efficiency of \( \leq 0.33 \) (Fish 1996). In addition, energy is lost in acceleration of the mass of the limb and the water entrained to the limb (Fish 1996).
When compared to aquatic animals, the structure of the limbs of humans further limits thrust production. The human hand is located at the end of a relatively long arm. Although such a design could enhance torque, the projected area of the hand is relatively small for thrust production. Aquatic animals that paddle maximise propulsive drag by increasing surface area by elongation of the digits and interdigital webbing (Fish 2004). In addition, the length of the limb is short to allow greater force production from the muscles. As these animals have a recovery phase that remains in the water, increased drag on the appendage is reduced by decreasing the area by adduction, feathering and decreasing the forward velocity of the appendage (Fish 1996).

The feet of humans also have a relatively small projected area and are moved through a small arc consequently affecting only a small mass of fluid for low thrust production. In addition, the degree of motion is limited at the ankle joint producing an asymmetry in thrust through the stroke cycle (von Loebbecke et al. 2009b). The most highly derived aquatic mammals (i.e., Cetacea, Pinnipedia, Sirenia) swim with high aspect ratio (span²/area) flippers or flukes by lift-based oscillation (Lighthill 1969; Fish 1996). These propulsors produce thrust by acting as hydrofoils with the lift vector inclined forward to derive a thrust component (Lighthill 1969; Webb 1975). Comparison of the dolphin kick in humans with the actual motion of dolphins showed that the efficiency of the human effort was lower with respect to the cetaceans (von Loebbecke et al. 2009a,b). Correspondingly, the vortex wake of the dolphin indicates high thrust that is produced symmetrically through the stroke cycle (Fish et al. 2014).

Prospectus

When compared to aquatic animals, human swimming performance is inferior due to limitations of morphology and physiology (Toussaint & Truijens 2005). An understanding of the mechanics of swimming in humans and non-humans alike can be used to push the performance envelope. Although there will be limits to the speeds that human can attain in the water, advances in training and technology may allow improvements in swimming speed.

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**Immune function and the swimmer: twenty-five years of enquiry at the AIS**

Peter Fricker

Chief Sports Medicine Advisor to the President of Aspire Zone Foundation, Doha, Qatar

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**Exercise, immunity and athletes**

Professor Peter Fricker

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**XII INTERNATIONAL SYMPOSIUM ON BIOMECHANICS AND MEDICINE IN SWIMMING**

APRIL-MAY 2014

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**The J curve**

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The graph shows the relationship between the risk of URTI (Upper Respiratory Tract Infection) and the amount and intensity of exercise. The risk is lowest in moderate exercisers, with the highest risk for sedentary individuals and those engaging in very high-intensity exercise.
Do elite swimmers experience more upper respiratory illness than non-athletes?
Fricker PA, Gleeson M, Flanagan A, Pyne DB, McDonald WA, Clancy RL
Clin Exerc Physiol 2000

Medical records of 97 male and female elite swimmers over 11 years compared with a survey of 9,014 members of a community (Douglas and Muirhead 1978)
Male swimmers (n=56) average 2.5 URI per year
Female swimmers (n=41) average 3.1 URI per year
Incidence of URI in the community 2.4 pa for decile 20-29 yrs and 3.0 pa for decile 10-19 yrs

Effect on immunity of long term intensive training in elite swimmers
Gleeson M, McDonald WA, Cripps AW, Pyne DB, Clancy RL, Fricker PA
Clin Exp Immunol 1995

26 elite swimmers (male and female)
Seven months pre-competition training
12 healthy active controls
Bloods – lymphocyte subsets, Ig subclasses
Saliva – Ig and albumin (24 hrs after previous training session)
Effect on immunity of long term intensive training in elite swimmers
Gleeson M, McDonald WA, Cripps AW, Pyne DB, Clancy RL, Fricke PA
Clin Exp Immunol 1995

Results
Lymphocyte subsets:
Over seven months NK as a percentage of total lymphocytes fell 35% (2.1% of cells)
NK cell numbers fell 57%
Salivary IgA and albumin:
Sal IgA decreased in swimmers over seven months and
decreased over each training session in swimmers (increased in controls)
Sal IgG and Sal IgM higher pre-training in swimmers and decreased after training in swimmers
Serum Igs:
Lower IgA, IgG(2), IgM (10th %ile), and IgG decreased with increased distance swum

Salivary IgA and infection risk in elite swimmers
Gleeson M, McDonald WA, Pyne DB, Cripps AW, Francis IL, Fricke PA, Clancy RL
MSSE 1999

26 male and female elite swimmers and 12 active healthy controls over seven months
Saliva collected pre- and post-training session
Daily exercise log (intensity, distance swum, “endurance/quality/taper”)
Psychological monitoring (Spielberger State-Trait Anxiety Inventory Form Y)
Daily infection (illness) log
Throat swab and culture for symptomatic upper respiratory illness
Salivary IgA and infection risk in elite swimmers
Gleeson M, McDonald WA, Pyne DB, Cripps AW, Francis IL, Fricker PA, Clancy RL
MSSE 1999

Results
No difference in infections between swimmers and controls
Significant correlation between pre-training Sal IgA and the number of infections in swimmers and controls
Lower pre-training Sal IgA associated with higher number of infections
Sal IgA declined over time in swimmers and controls

FIGURE 3 - The relationship between resting saliva IgA concentration and incidence of infection among 26 elite swimmers during a 7-month training season. Resting IgA fell during the 7-month training period on average by 4.1% per month of training and infection incidence was more frequent towards the end of the training period. Data from Guzzino et al.3
Valtrex™ therapy for Epstein-Barr virus reactivation and upper respiratory symptoms in elite runners
Cox AJ, Gleeson M, Pyne DB, Saunders PU, Clancy RL, Fricker PA
MSSE 2004

EBV proposed as a cause of upper respiratory symptoms (URS) in high performing athletes (Gleeson et al., MSSE 2002)
EBV persists in health in epithelial cells and B lymphocytes of the oropharynx
Transient immunosuppression associated with intense exercise may open the window for EBV reactivation
Valtrex (valacyclovir) prevents replication of herpes group viruses and reduces shedding in saliva (Andersson et al., Infection 1987)

Valtrex™ therapy for Epstein-Barr virus reactivation and upper respiratory symptoms in elite runners
Cox AJ, Gleeson M, Pyne DB, Saunders PU, Clancy RL, Fricker PA
MSSE 2004

20 male elite distance runners (18.8-29.7 yrs) in a double blind placebo controlled trial. Valtrex 500mg twice daily and placebo, one month treatment with washout
Weekly saliva collection over the study period and analysis for Sal IgA and EBV Daily illness log, training log, medical review for URS episodes
**Valtrex™ therapy for Epstein-Barr virus reactivation and upper respiratory symptoms in elite runners**
Cox AJ, Gleeson M, Pyne DB, Saunders PU, Clancy RL, Fricker PA
MSSE 2004

**Results**
Trend for lower Sal IgA with URS
5 of 12 seropositive runners had no detectable EBV in saliva throughout study
On Valtrex 1 of 12 seropositive had detectable EBV in saliva
No effect on reducing URS with Valtrex

**Conclusion**
Valtrex reduces reactivation but is not effective in limiting URS in runners

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**Incidence, etiology, and symptomatology of upper respiratory illness in elite athletes**
Spence L, Brown WJ, Pyne DB, Nissen MD, Sloots TP, McCormack JG, Locke AS, Fricker PA
MSSE 2007

63 elite and recreationally competitive athletes (triathlon, cycling) and 20 sedentary controls (18-34.1 yrs) studies over five months (Summer, Autumn)
Nasopharyngeal and throat swabs for two or more symptoms at once
Microscopy, culture and PCR
Wisconsin Upper Respiratory Symptom Survey (symptomatology and functional impairment)
Incidence, etiology, and symptomatology of upper respiratory illness in elite athletes
Spence L, Brown WJ, Pyne DB, Nissen MD, Sloots TP, McCormack JG, Locke AS, Fricker PA
MSSE 2007

Results
37 episodes in 28 subjects
Infectious agents in 11 of 37 episodes
Most common pathogen *rhinovirus* (then *S. pyogenes, H. influenza, S. aureus*)
Symptoms worse, functional impairment greater with infectious pathogens
Higher rate of URS amongst elite athletes than recreational athletes

Spence et al., MSSE 2007
Cytokine gene polymorphisms and risk for URS in highly trained athletes
Cox AJ, Gleeson M, Pyne DB, Callister R, Fricker PA, Scott RJ
Exerc Immunol Rev 2010

Not all URS in athletes are infections, non-pathogenic inflammation may be the cause

Pro- and anti-inflammatory cytokines differ between healthy and illness prone athletes (Cox et al., MSSE 2007)

Can genetic markers (Single Nucleotide Polymorphisms) be used as indicators of risk for URS in athletes?

Cytokine gene polymorphisms and risk for URS in highly trained athletes
Cox AJ, Gleeson M, Pyne DB, Callister R, Fricker PA, Scott RJ
Exerc Immunol Rev 2010

170 male and female elite athletes (16.8-34.0 yrs)
Two groups:
healthy athletes (two or less episodes of URS in previous year) (n=82)
illness prone athletes (three or more episodes of URS in previous year) (n=88)

Salivary samples examined for eight cytokine SNPs:
IL-6, IL-8, IL-10(G), IL-10(C), IL-1RA, IL-2, IL-4, IFN-gamma
Cytokine gene polymorphisms and risk for URS in highly trained athletes
Cox AJ, Gleeson M, Pyne DB, Callister R, Fricke PA, Scott RJ
Exerc Immunol Rev 2010

Results
IL-6 genotype GG (cf. GC and CC) higher expression (20% frequency) in illness prone group compared with healthy group (9%)
IL-4 low expression in illness prone group (78% frequency cf. 65% in healthy group)
IL-2 (CC cf. CA plus AA combined) high expression associated with decreased likelihood of frequent URS (p=0.06)

Conclusions
IL-6 high expression with pro-inflammatory action may contribute to non-infectious presentations of URS
IL-2 high expression induces T-cell activation and clonal expansion, enhances cytolytic activity and further cytokine production (antiviral effect)
The role of IL-4 is unclear
Characterising the individual performance responses to mild illness in international swimmers
Pyne DB, Hopkins WG, Batterham AM, Gleeson M, Fricker PA
Brit J Sports Med 2005

Does illness affect performance?

72 male and female elite swimmers (15-27 years)
133 swimming performances over three consecutive calendar years (including international competitions)
Performances assessed by FINA IPS
Illness (RT,GIT, systemic etc) monitored over six weeks of taper and competition each year
Healthy compared with ill in study periods

Results

Illness reported in 35% of international performances in males, 38% in females
48 performances associated with illness

Mild illness has a substantial though small harmful effect in males (perhaps 0.5 sec over a 200m race)
Probiotics and immune response to exercise
Pyne DB, West NP, Cripps AW
Am J Lifestyle Med 2012

Metagenomic sequencing has revealed individuals appear to have a core group of gut bacteria......the "core microbiome"
Nutrients can exert substantial influence
Intestinal bacteria influence health and disease (obesity, inflammatory bowel disease, diabetes)
Probiotics and immune response to exercise
Pyne DB, West NP, Cripps AW
Am J Lifestyle Med 2012

Probiotics and athletes
L. casei, L. fermentum, L. acidophilus, L. rhamnosus most often studied in athletes
L. acidophilus reversed a drop in T-cell secretion of INF-gamma in fatigued athletes after four weeks (Clancy et al., 2006)
L. fermentum in endurance male runners halved the number of days of respiratory symptoms over four months (Winter season), and reduced the severity of symptoms (Cox et al., 2010)
Probiotics and immune response to exercise
Pyne DB, West NP, Cripps AW
Am J Lifestyle Med 2012

Probiotics and athletes
L. fermentum over 11 weeks in physically active adults reduced respiratory and GI symptoms in males, but not females (West et al., 2011)
This was associated with small perturbations in pro- and anti-inflammatory cytokines (IL-1RA, IL-6, IL-8, IL-10, GM-CSF, IGN-gamma, TNF-alpha)
"Taken together.....studies in athletes provide modest evidence that probiotics can provide substantial clinical benefits in highly active individuals.
......there is little consistency in outcome measures and in the selection of measures of immune function. More studies are needed to resolve these...”

So what have we concluded?
Training is associated with dose responsive and cumulative immunosuppression
The risk of upper respiratory illness may be linked to changes in immune status
Not all upper respiratory symptoms are infectious in origin
Mild illness can affect performance adversely in high performance athletes
There are genetic markers which may indicate risk of infection
Interventions such as anti-viral agents have not proved effective
Interventions with probiotics show promise in enhancing immune status
The development of a research department in the French Swimming Federation: a paradigm evolution

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Keywords: strategy, theory of the complex systems, research and testing in swimming, support and assistance to coaches, scientific team management

Abstract
The French national swimming team won 66 Olympic and World medals from 1998 to 2013, although it had won only 12 between 1984 and 1998. The growth of the French Swimming Federation’s...
research department since 1998 has been one of the factors contributing to this success. The development of this department was a complex undertaking for many reasons. First, French swimming coaches and technical staff have not been trained within a scientific culture. Yet the coaches and staff possess extraordinarily diverse skills that in many ways depend on their personalities, personal histories, cultural background and past training experiences. This diversity highlights the need for widely differentiated and individualised scientific support. Second, the department’s activity is expected to cover the broad range of issues related to training and high-level performance. This has required a multidisciplinary approach and the development of a well-functioning collaborative network. Last, as part of our mandate, the research department is called on to communicate and share our findings with all French territories. The first objective of the department is to formalise the most effective training practices through an analysis of coaching practices. The second objective is to build knowledge that is relevant to all issues touching on performance and health, such as motor learning, nutrition, the mobilisation of energy resources, altitude training, biomechanics and any other area related to high-level training. As a third objective toward performance optimisation, the department of research has for the past 15 years been piloting the development of technological processes to evaluate performance. This aspect of our activity has resulted in the development of high-tech tools and research equipment that have been meticulously constructed and shown to be well adapted to use in the field. In these three areas, the analysis of the most effective practices, knowledge building to enhance training, and the development of technologies for practitioners, the research department of the French Swimming Federation has been a leader in developing ideas, innovations and skills over the last 15 years.

The institutional context at the time the department was created

In 1996, the world of French swimming was characterised by lacklustre performances and an powerful movement toward change and new beginnings was slowing taking shape. The French team had won no medals at the 1994 World Championships in Rome or the 1996 Olympics in Atlanta. The arrival of a new technical director, Mr Clémençon, and a new head coach, Mr Fauquet, signaled the start of a new era for French swimming as both men brought progressive thinking and a spirit of innovation to their jobs. The relationships between the French Swimming Federation and university research units had not been very fruitful up to that point. The university researchers organised their studies without much consultation with the Federation (1 or 2 meetings per year), and their research interests were far removed from the concerns of the coaches. The research was not multidisciplinary, did not take into account experiential knowledge (the coaches’ practical know-how), and was not oriented toward the transfer of skills or technologies. With little exaggeration, one might say that despite the high cost to the French Swimming Federation, we saw our partners only twice a year in the context of testing or the supervision of doctoral theses and we possessed nothing in the way of practical tools. Given this state of affairs, we decided to become autonomous. This choice in no way meant that we were closed to the idea of exchanges with outside institutions. Instead, we borrowed Dupuy and Varela’s conception of autonomy (Dupuy 1985, 1986; Varela, Maturana et al. 1974, 1987) which simply meant that the Federation would not take instructions from the environment (the university) but would instead become better adapted to this environment through growth. This was a pivotal decision: we set out both to differentiate ourselves from the world of conventional academia and to find a way to build better bridges to it.

The new Federation technical director presented a project and the new head coach expressed both his hopes and needs for the future. We listened closely and then began defining the major orientations for a research department within the Federation. Our main objectives were to tackle the most important training issues through a solid knowledge of the extant literature and our own experimental studies, and to develop new technologies for evaluating the various aspects of performance. Another important objective was to contribute to the training of coaches by building the training contents and following the coaches in their work with the swimmers.
Today, in 2014 the research department is fully independent with an annual budget of 130,000 euros (70,000 in salaries and 60,000 in operating expenses) and three staff: myself and two assistants, all with PhDs or engineering degrees. Here are a few figures that give a better idea of our output: 4 PhD students and 17 Master's degree students have been supervised; 8 books, over 100 articles for coaches, 21 research articles, and 50 articles published in the proceedings of international conferences; 300,000 euros invested in equipment; and every year over 100 days spent out in the field assisting coaches.

**The theoretical framework for the department: Conceptual and epistemological orientations**

Readings from the philosophy of science have profoundly influenced our choices. We heeded Gaston Bachelard’s (1938, 1985) warning that, although scientific knowledge is set up in opposition to common sense, it becomes sterile once it is assumed that science provides definitive answers (Chimiso 2001). The works of Popper (1934, 2002) oriented us toward the methodological approaches best suited to understanding the relationship between scientific models and real phenomena. For this philosopher of science, a scientific proposition is not a verified proposal (i.e., with certainty) nor is it verifiable by experience (i.e., through scientific testing); instead it is rebuttable (or falsifiable) and thus we cannot never state that it will never be refuted. These two philosophers have greatly influenced our conception of working with coaches. For example, in our work of assisting the coaches of the French swimming team, we constantly seek to match their practical know-how and their highly sensitive empirical knowledge with our scientific knowledge and experimental findings (Ericsson et Smith 1991). This ongoing process of comparison has helped us to build models that are never assumed to be definitive but rather conjectural, and thus we continue to seek to refute them, more fully develop them, or refine them (Deleuze et al. 1996).

In the goal of assisting these elite coaches, we have also chosen to emphasise multidisciplinary research (physiology, motor learning, movement analysis, recovery and nutrition, altitude training) because these top coaches themselves raise many questions about how the multiple factors that they deal with are connected. For example, coaches ask questions about how strength is best developed and how increasing strength affects stroke technique and energy expenditure during a race. We have found that it is vital to respond quickly and appropriately to these kinds of questions about the many interactive aspects of their work in order to remain credible. This need has in fact led us to organise our research from a multidisciplinary perspective, and the model presented in Figure 1 reflects this commitment. It defines the four elements (or subsystems) that interact and compose the high-performance system: athlete, training, performance and coach. We also try never to lose sight of the ultimate goal in building a knowledge base (Lemoigne 1986): knowledge is not built as an end in itself but always in the service of optimising performance. For example, our mission is clearly to contribute to the excellence of the French Swimming Federation and we therefore strive to enrich and strengthen the Federation’s cultural context, which for us means that we give as much importance to teaching (transmitting knowledge to the coaches) as we do to research (building scientific knowledge). With experience, we came to realise that the only way to really assist the coaches was to incorporate the various research fields (nutrition, motor learning, energy metabolism, swimming biomechanics) into a project of overall and contextualised performance enhancement (e.g., transforming the technique of a given swimmer in a given cultural context and at a particular moment in his or her history in order to achieve a specific performance). From these field experiences and based on Morin’s complexity theory (2005), we distinguished four paradigmatic levels to guide our action: scientific complication (abstract and decontextualised), vague globalisation (imprecise and without content), restricted complexity (taking into account interactions and unpredictability), and generalised complexity, which incorporates the three underlying levels. This generalised complexity gave rise to a project that is contextualised and open to a field of possibilities. Over the past 15 years, we have explored these four levels and defined their contributions and limitations.
The first phase: 1995-2000. First actions of the research department: monitoring and documentation

In 1995, the Federation project was to build a knowledge base because no such base existed. The most innovative aspects of this project were (1) the constant linking of research findings and practical know-how from the field and (2) an eclectic and multidisciplinary perspective on all aspects of high-level performance and training. Within three years, an 800-page baseline document covering all aspects of training and performance was published (7000 copies), representing our collaborative work with 20 coaches, researchers, and educators as co-authors. Similarly, in 2005 the Federation organised an international conference on swimming in collaboration with the International Amateur Swimming Federation (FINA) and the National Institute of Sport, Expertise and Performance (INSEP), which brought together 138 coaches, researchers, and educators as speakers. These actions have continued through the years with the release of several DVDs on physical preparation, technical learning, and swimming techniques, as well as the development of our website featuring 600 documents available to all French coaches.

Although this work has been important, the impact of monitoring and knowledge dissemination has gradually declined over the years. Their contribution to transforming coaching practices was sometimes limited because the knowledge had been built by professionals who were not coaches (e.g., researchers), in contexts other than performance, and sometimes with other objectives (e.g., for publication). We observed that, in order for new knowledge to be fully incorporated and mobilised by the coaches, the coaches needed to be deeply implicated in the research and this research had to be based on what the swimmers’ did in their everyday contexts. In addition, the rise in quality in both the coaches and swimmers (8 medals at the World Championships in Perth 1998 and Barcelona 2003, and 7 medals at the Olympic Games in Sydney 2000 and Athens 2004) has led to new needs and new
demands. To help support the French team in reaching the highest international level, the Federation was asked to intensify support to the coaches in the field. The observation of our competitors (Australia, the UK, Japan) also revealed that they recruited sports scientists to assist their coaches in the field. To meet these demands, we therefore decided to develop our in-house scientific and technological skills.

The second phase: 2000–2008. The department’s necessary orientation toward science

The research department of the French Swimming Federation was officially created on 21 April 1999. This decision was prompted by the policies of the Ministry of Sports at that time and the Olympic preparation team, which was pushing for the creation of a research department within each sports federation. We were utterly convinced that if the French swimming team was to become one of the best in the world, every Federation department would first have to become one of the best. To reach this goal, we had to develop our skill set and find the necessary resources and means. We adopted a systemic perspective to develop the department and integrated all research fields associated with swimming performance. The following eight major research themes were chosen: the analysis of expertise, expert coaches’ practical know-how, competitive performance, training and swimmers’ adaptation processes; modeling the relationship between training and performance and between training and swimmers’ adaptations; and motor learning in swimming. This orientation meant that we needed to develop skills in literature searches, experimental procedures, the use of computer and statistical tools, and research publication. Most importantly, this orientation helped us to extend and diversify our functions within the Federation, which has turned out to be crucial in the current context of funding cuts in Europe. We have obtained ministerial and regional grants for 18 research projects carried out in partnership with 22 academic institutions, for a total funding of 900,000 euros. We have supervised four PhD candidates (1 alone and 3 in collaboration) and 22 Master’s students.

This phase of developing a more scientific orientation was quite long and we sometimes felt that we had strayed from the concerns of the coaches and were never quite close enough to the basic needs of our university research partners. We seemed to be constantly torn between scientific rigor and practical relevance (Schön 1994; Von Krogh 2000). Today, however, the performance optimisation unit can respond quickly to any issue on training and swimming performance. This general excellence is also reflected by many publications and has been accompanied by some very successful technological developments that are now routinely used by the coaches.

Technological developments: tools for coaches

The successive Federation technical directors have all supported the development of a research department that serves the needs of coaches. In practice, this has meant that we needed to figure out how to be very discreet poolside, without disrupting the training sessions, and ready to turn over our results in under 30 minutes after taking measurements and in language that would be easily grasped by the coaches. We thus defined four areas of intervention: on-site evaluation of competitive performance, evaluation of starts and turns, evaluation of acceleration and intracyclic speed coupled with video analysis, and physiological evaluation during swimming. Many technological tools were already at hand (software analysis of performance or the moment of inertia, portable gas analyzers), and all we needed to do was refine them for greater speed, reliability and relevance. To this end, we worked with several private high-tech companies.

The response to these technological modifications has so far been very positive. They were much appreciated during the last two Olympics, and the coaches report that they have helped them to develop and refine their mental representations and coaching skills. During the course of preparations for the next Summer Olympic Games, some of the coaches have nevertheless confided that the poolside measurements are not made often enough and therefore are unable to inform on the training effects over time. They in fact would like to use the assessment tools continuously. In
response, we have developed instruments that allow additional measures. We are also building two high-performance pools, similar to the Canberra model, that will be ready in September 2014.

The mode of intervention with coaches

We spend about 100 days a year in the field working alongside the coaches and other staff of the French swim team. We are present in many different contexts: during routine training and the final preparations for competition; at national, intermediate or international meets; with the entire French team together or during visits to the various training locations; in situations of relative success or failure; and in situations marked by a spirit of cooperation or tension. Theories from management science, education, occupational psychology and clinical psychology have contributed to the theoretical framework that underlies our conception of assistance to coaches (Jaques 1994; Von Krogh 2000). In many of the works dealing with professional training, a distinction is made between information, know-how and knowledge (Gouzien 1991; Lerbet 1995; Schön 1983; Von Krogh 2000). According to these authors, information is external to coaches and consists of all the data collected on a given topic (e.g., the scientific corpus). In contrast, knowledge is the actual experience of knowing in a given context and in that sense it is completely integrated and controlled by the practitioner. It is emotional and cognitive and contributes to the coach’s identity. Between information and knowledge is know-how, which is all the information that the coach takes in and organises. Information thereby acquires meaning and becomes knowledge when the coach integrates and connects it to a personal meaning system, deeming it useful and desirable from the perspective of a personal value system and the professional context. The works of Gouzien (1991) and Lerbet (1995) highlight the limitations of content exclusively formalised as information (scientific knowledge) or knowledge (professional knowledge). In the first case, scientific information is not meaningful for professionals in the field and, in the second case, the repetition of an experience eventually leads to the loss of meaning and to stereotypical professional behavior and the corresponding lack of self-questioning or, to use Schön’s term, meta-reflexivity (1983). We observed that coaches are able to reach higher levels of organisation by integrating these two poles (information and knowledge) through the know-how they build on the basis of professional action. Our strategy is thus to give primary importance to coaching know-how and skills. In addition to the opportunities for training offered by the analysis and formalisation of coaching practices, this approach allows us to further capitalise the coaches’ experiences to conceive new training materials. We also take advantage of our visits to Olympic training centers to extensively film (using a professional cameraman) the coaches’ interventions and all our exchanges with them. The purpose is to assemble the wealth of elite coaching skills and techniques and ensure that it circulates among the national coaches and to all French coaches (Rogers 2003).

Several theories from management science, social psychology and vocational training have guided our work with the coaches. For example, we do not refer to challenges nor do we express high expectations in our discussions, we check regularly to be sure that the coaches feel comfortable with our presence and our work, we weigh the pros and cons of each technical option that a coach choses, we take into account the body of knowledge and experience accumulated in each area of focus in the discussions, we build connections between technical, physiological and training aspects of swimming, we translate scientific knowledge for the coaching culture, and we try to build coaching strategies that are sufficiently detailed over a realistic time scale. We close all discussions by summarising the main points and we make sure the coach has documents that clearly illustrate the scientific or technical issue under discussion. Last, sharing our interpretations of the poolside technical evaluations is a powerful means for transforming the coaches’ ideas. These evaluations are made with highly efficient and rapid technological tools in the training or competition situations selected by the coaches themselves. At these moments, when technical evaluations are being made, the two worlds of real life and scientific research come together and allow us to build a bridge between the detailed information derived from scientific theory and the rather vague and opaque knowledge acquired in the field (Schön 1983). Moreover, these situations and the discussions that they prompt help us to adapt scientific knowledge to unique and individual situations. A guiding principle of our work is
adaptation to the individual characteristics of the coaches. Their skills depend greatly on their culture and past training, and are constantly evolving. The staff of the French team is a veritable rainbow of diversity. We have found that the coaches have personalities of great richness and yet each one is so distinct. Their training histories are so vastly different at times, and they often work in very different environments and contexts. They may differ in age by as many as 20 years and often have very different lifestyles. Some left school at a very young age and worked their way up through the club system, whereas others are university-trained educators who have been posted to a training center. Yet, despite all these differences, the coaches have a lot in common: they never lose sight of their objective and they are rigorous, demanding, hard-working and highly analytical. We therefore try to be attentive to all aspects of their significant differences, whether they be cultural, educational, intellectual, or contextual. These elite coaches are not in their positions by chance, so we always try to focus in on their passions and the very best of their skills. By doing so, we see the best in them and connect with it. We also place high value on the originality of their knowledge and know-how and make this the starting point for our proposals. We believe that this attitude helps all of us to develop a spirit of acceptance of ‘otherness’, which is an essential condition for effective teamwork and one of the best ways to avoid conflict. We adapt our perspective, our way of speaking, our attitudes, our actions and the scientific knowledge that we bring with us according to the personality of each coach. In only one way do we refuse to adapt: we never lose sight of our ultimate goal, which we know to be the same for all of us: to be as effective in our work as possible while adhering to high ethical standards. Whatever our interactions with the coaches, we always try to meet the standard of excellence that they themselves convey: commitment, hard work, and quality.

Conclusion

The French Swimming Federation is today at a turning point in its history. Although the French team has now demonstrated its ability to compete with the biggest countries in the world (the United States, Australia, China), the number of elite swimmers remains low compared with Australia, for example. Therefore, one of the major components in the plan of the current national technical director, Lionel Horter, is to increase the number of elite swimmers. To this end, three decisions have been made: to increase the number of clubs and high-level training structures everywhere in France, to include more young swimmers in the French teams, and to create a collective of swimmers and coaches on the model of the workshop organised by the Australian Federation in February 2013 on the Gold Coast (140 swimmers organised by specialty groups and 30 experienced and apprentice coaches). These decisions mean new needs in terms of support and scientific monitoring. The French successes in the last two Olympics, along with the very positive socioeconomic and media impact, have attracted many scientists to the field of swimming and their work probably needs to be coordinated. Last, around the world the quality of scientific support is increasing, as evidenced by the excellence of the work presented here at this Congress. Our duty is to remain among the leaders in this field.

References

Water competence: new insights into swimming and drowning

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Abstract

Langendorfer and Bruya (1995) originally proposed ‘water competence’ as a gender-inclusive alternative to ‘watermanship’, to describe aquatic expertise broadly conceived. Other authors (e.g., Stallman, et al. 2008; Moran, et al. 2011) have suggested water competence as minimum performance required to reduce drowning risk. I propose that contemporary science requires envisioning human aquatic performance, learning, and instruction uniquely by associating water competence with five key principles: 1) dynamic; 2) individual; 3) task-related; 4) contextual-probabilistic; and 5) developmental. It is critical to view water competence dynamically, specifically using Newell’s (1986) constraints model, rather than from static ‘ability’ conceptions. Water competence views efficient and effective control and coordination of aquatic tasks as resultant of interactive relationships among individuals’ personal characteristics, specific aquatic environments in which persons find themselves, and unique task demands required. The dynamic developmental view argues against a unitary approach to swimming instruction or to drowning prevention efforts. It should embrace the notion that individual capabilities emerge in semi-predictable orders across the lifespan as well as moment to moment and from one aquatic situation to the next. Because it recognises the complexity of water competence, I argue for engaging lines of scientific ‘strong inference’ (Platt 1964) to explore how persons, aquatic environments, and task demands interact, while searching for the existence of lawful, yet heuristic, principles by which to guide our clinical and professional behaviors in swimming and aquatics.

Keywords: water competence, swimming, drowning prevention, water safety

Theories of change and aquatics

For over 150 years, we have studied how humans acquire movement and become ‘skillful’. At least three different world views have shaped how we think aquatic motor skills such as swimming come to be: nature (a.k.a., maturation), nurture (a.k.a., learning), and systems (a.k.a., ecology or chaos). The nature perspective presumes we learn to swim because it is an innate capacity with which we are born. McGraw’s (1939; 1945) swimming reflex is sometimes cited as an example (see Figure 1A). The nurture view assumes that in order to be able to swim, we must learn through specific, structured experiences. This metatheory obviously is the most widely accepted, especially by agencies and...
organisations that offer swim lessons because they believe one learns to swim only by being explicitly taught. The third and most recently-identified way to understand swimming skill acquisition is via a systems approach, sometimes known as ecological or chaos theory (Gleick 1987). In this less-well understood approach, we are able to swim as a result of complex interactions among a person’s individual capabilities, the qualities of the aquatic environment, and the demands of the specific aquatic task one is attempting (see Figure 2) (Newell 1986). I believe that this third world view provides us with the best way to really appreciate and investigate both drowning prevention and water competence.

The tragedy of drowning is a worldwide pandemic particularly among the low and middle income countries (LMIC). The annual numbers of fatal drownings in the U.S. and many other high income countries (HIC) have slowly declined over the past 30-50 years while the estimated worldwide numbers remain at staggering high levels. Informed estimates of annual fatal drownings range between 200,000 to 800,000 lives lost, of which most (i.e., at least 300,000) occur in the LMICs especially those in tropical regions such as Asia and Africa where water is omnipresent particularly during the rainy or monsoon seasons. Moran’s (2010; 2012) insightful articles describing drowning as an ‘iceberg phenomenon’ wherein estimates suggest that non-fatal drowning (the preferred term the International Life Saving Federation strongly urges instead of the older and less accurate ‘near drowning’) may occur at a ratio of 10:1 in relation to fatal occurrences. Another informal survey found a majority of respondents to have had or know of a ‘near’ or ‘non-fatal’ drowning experience at sometime during their lifetime. We need to heed this projected high rate of non-fatal drowning because the difference between non-fatal and fatal may be less than a minute and some fortuitous occurrence such as bystander being able to respond (Moran & Stanley 2013).
Applying theory to drowning prevention

The Centers for Disease Control and Prevention (CDCP) in the U.S. and the U.S. Consumer Product Safety Commission (USCPSC) have proposed a nurture solution through the use of ‘multiple barriers’ between water environments and prospective drowning victims, particularly young children, ages 1-5 years. Young children represent a worldwide group that consistently experiences the highest rates of both fatal and non-fatal drowning. Despite recognising that drownings are a multi-factorial phenomenon best addressed through a systems approach, nurture only reshapes the environment using barriers rather than considering the full complexity of drowning experiences. Of course, the well-intentioned use of passive barriers is appropriate to home environments in HICs, not in LMICs where fatal and non-fatal regularly occur in natural bodies of water that cannot be isolated using simple barriers. Recognition of the complexity of drowning factors is indeed a critical realisation, albeit only a first step in a long journey for drowning prevention advocates, researchers, lifeguards, water safety experts, and other clinicians.

Applying theory to water competence

Bruya and Langendorfer (1995) proposed and then expanded upon a new way of viewing what it means to be able to minimally survive as well as perform optimally in a water environment. When we originally suggested ‘water competence’ as a gender-inclusive alternative to ‘watermanship’, an old concept describing broad aquatic expertise (originally applied in boating), we did not fully appreciate the full metatheoretical implications for our proposal (see Figure 2). Recently several authors (e.g., Stallman et al. 2008; Moran et al. 2011) have explored various conceptions of water competence (e.g., term to address the minimum performance requirements to reduce drowning risk). Both our original and the recent ideas will benefit from a full appreciation of water competence from a systems perspective.
Role of water competence and learning to swim in drowning prevention

Having sufficient swimming skillfulness (a.k.a., ‘ability’) seems like a ‘no brainer’ in the quest for a ‘magic bullet’ in preventing drowning; however, learning to swim may be necessary, but not sufficient to prevent drowning. Without a theoretical appreciation for how and why we swim or fail to swim (a.k.a., drown), we cannot make important strides in addressing issues associated with what it means to swim or to demonstrate water competence. I believe the first step is to accept how complex the processes associated with swimming, water competence, and drowning prevention and secondly, to realise that simplistic nature or nurture theories. In the next several sections, I describe the five key principles (i.e., dynamical, individual, task-related, contextual-probabilistic, and developmental) associated with water competence that flesh out its qualities and potential for enhancing our knowledge of learning to swim, optimising swimming performance, and reducing drowning risk.

Water competence as a dynamical system. Earlier in the paper (see Figure 2) I proposed a radical proposition that skill or competence (sometimes inaccurately termed ‘ability’) in swimming is not a capacity possessed in any static or permanent way by any individual. Our common way of speaking about our skillfulness in the water, ‘Yes, I can swim’ or ‘No, I can’t swim’, reveals our collective traditional way of thinking about swimming as something we possess within our person. Applying dynamical systems theory, we can understand ‘swimming’ or ‘water competence’ as an emergent and potentially transient systemic behavior, mediated by interactive relationships among swimmer’s individual characteristics, their perceived swimming task goal(s) at any point in time, and the aquatic environmental context(s) in which one finds him or herself. In other words, competence to swim or even to avoid drowning depends upon what I am intending to do and where as well as my individual capabilities. For example, if I am trying to survive in a rip current in open water or to swim 100 meters in a Masters competition in a pool, my swimming actions likely ought to be quite different. In both cases, I ‘can swim’, but I will do so very differently. How fast I complete the 100 meters depends upon the stroke event in which I am competing, the length of the pool and lane, and certainly my current level of physical conditioning. I realise that this may seem like mincing words or putting too fine a point on a subtlety, but it really is an important theoretical distinction when trying to understand a different perspective regarding what differentiates ‘being able to swim’ in the context of water competence and drowning prevention.

Water competence as individually unique. Individual characteristics at the peak angle of the triangle represented in Figure 2 illustrate the personal qualities that humans bring to aquatic endeavors. These include a person’s physical size, body segment relative proportions, their body composition, their force production capabilities, fitness levels, physiological capacity, the state of the nervous system including consciousness, and a host of other relevant personal abilities/disabilities. One of my brothers often laments that if he and I had been at least 6 inches (15 cm) taller then he believes we could have been even more successful as competitive swimmers. Nine years ago before I participated in a successful WeightWatchers regimen and lost 35 lbs. (16kg), I floated much higher in the water, but the increased body mass also produced greater resistance in the water and lower physiological functioning when I competed in Masters. In the intervening years, I actually have reduced my resting heart rate through training, but I have lost 8-10 bpm on my maximum heart rate plus shoulder strength due to two surgeries, resulting in substantially slower competitive times, more so in the sprint than distance events (you can verify this by looking at my individual swimming times online at USMS.org). All of these examples illustrate how unique individual qualities interact to alter swimming performance plus potential risk of drowning as well.

Several studies have pointed out that drowning is not unique to young children or persons who may be considered ‘non-swimmers’. One Norwegian study pointed out the paradox that sometimes even so-called ‘good swimmers’ drown (Hindmarch & Melbye 2011). If one presumes that swimming skill is a static personal ‘possession’ or ‘ability’ (under either the nature or nurture perspective), then it is almost inconceivable that a strong swimmer should drown. If, however, one understands that ‘swimming’ is an emergent and dynamic state of behavior dependent not only upon certain individual characteristics such as sufficient buoyancy, fitness, body proportions, and a state of consciousness, as
well as sufficient and prior experience in the water and motivation to swim, plus the presence of a water environment, then one might come to appreciate that as individual characteristics, motivation, and water conditions change, the state of ‘being able to swim’ can change dramatically and rapidly.

**Water competence as task-related.** The bottom left angle of the triangle in Figure 2 represents the task factors associated with humans in or under the water which may include the swimmer’s implicit or explicit goal (e.g., to stay afloat vs. traveling as fast as possible), presence of small equipment (e.g., goggles, nose plug, kickboard, hand paddles, wet suit, or even clothing), and any relevant external expectations or rules (e.g., competitive stroke rules, pool rules). Neither the nature nor the nurture theories adequately address how task characteristics may influence a person’s performance in the water. It is quite apparent to almost anyone that wearing street clothing can be detrimental to one’s ability to move through the water without added resistance. At the same time, clothing can provide some advantage as an insulator in cold water and can actually improve one’s flotation if air purposefully or accidently is trapped inside clothing.

In the context of swimming lessons and drowning prevention, it is important for agencies and instructors to appreciate that task characteristics clearly have a strong potential impact on one’s water competence. In fact, it is critical that when considering the specific tasks that swimmers practice, the broadest possible task characteristics ought to be experienced in order to increase the likelihood of transfer of learning. As with the clothing example above, if swimmers never experience swimming clothed, it reduces the probability of their success when immersed unexpectedly while clothed. It does not mean that a swimmer will automatically drown if they go in with clothing, but it does increase the probability and thus the risk.

**Water competence emerges from probabilistic contextual constraints.** As noted earlier, Figure 2 represents a modification of Karl Newell’s (1986) ‘constraints’ model of motor coordination and control as I have adapted it for studying swimming and aquatic activity. The bottom right angle of the triangle represents the conditions of the aquatic environment including the type of facility or open water, the water depth, the water and air temperature and relative humidity, waves and currents, and even the presence of other aquatic life (e.g., stingers, sharks, seaweed). In a similar manner to task characteristics, the aquatic context is a critical element in understanding one’s water competence.

Most importantly, each of the three factors in this model of swimming or drowning prevention are ‘connected’ or ‘linked’ to each other by the sides of the triangle, representing the so-called ‘constraints’, or relationships among the factors. According to Newell, it is the relationships among the individual, task, and environment from which emerge specific behaviors such as sustaining oneself in the water or conversely, drowning. The downward arrow coming from the center of the triangle suggests different outcomes or movement competence result depending upon the specific constraint relationships that exist. For example, if a healthy, fit and appropriately-experienced individual enters a guarded pool with the intention of lap swimming, the model suggests that a certain kind of behavior will be observed. Because individuals with a great deal of experience in the water reliably can evoke these predictable behaviors, typically swimming strokes, this is why such an individual is likely to claim ‘I can swim!’ Conversely, if the same individual unintentionally falls into a Class 5 white water without a PFD, very different outcomes of either swimming or drowning may emerge. Certainly if the same individual falls into any body of water while unconscious, it is most likely that drowning behavior will emerge. Regardless of how well we arbitrarily say the person ‘can swim’, it is this complex set of interacting constraints that shapes different sets of probabilities toward swimming and/or drowning.

**Water competence as developmental.** The final principle related to water competence actually subsumes the previous four. Dynamical systems essentially are developmental and the developmental perspective strongly supports viewing behavior as dynamic. I have written fairly extensively elsewhere (Langendorfer 2010; Langendorfer & Bruya 1995) about applying the
developmental perspective to aquatics. When we focus on the motor behaviors of humans in the water and how they may change over the lifespan or portions of the lifespan, we likely are adopting a developmental perspective. We know that swimming behaviors change in a regular, semi-predictable order over time (e.g., see Figure 1). We also realise that because these behaviors are the products of a dynamical system, they may change from moment-to-moment as well when either a person’s characteristics (e.g., their consciousness) or the task demands (e.g., swimming clothed) or the aquatic environment (e.g., cold water) shifts rapidly or unexpectedly, thereby altering the relationships (a.k.a., constraints). This is why I believe so strongly that we must not continue to consider water competence as a static ‘ability’ that a person acquires and forever afterward possesses. Nothing can be further from the truth.

**Water competence and infant drownproofing programs**

As a final illustration of the folly and danger of understanding water competence as a static ability, I would like to illustrate what we in the U.S. have referred to as infant drownproofing lessons. I anticipate many readers have seen one of the widely-circulated internet videos showing a young child clad in pajamas who opens the sliding door at the back of his house and wanders to the unfenced backyard in-ground swimming pool. Seeing a floating beach ball in the pool, the child tries to retrieve it, loses his balance, and plunges into the water. Apparently the video intends to illustrate how fortunate that child was because he had been ‘taught’ how to roll over onto the back and placidly float until help arrives. Authors of the video presumably expect that well-meaning parents, caregivers, or grandparents of young children will not be familiar with the importance of the American Red Cross Circle of Drowning Prevention that advocates close and active parental supervision as well as the use of multiple barriers to a pool such as a four-sided fence with childproof locked gate, childproof lock on the exit door, or a pool alarm or cover (none of which were present in the video scenario). The video authors instead want viewers to accept their claim that the ‘drownproofing’ program is both necessary and sufficient to prevent any child from drowning under the presumption that the young child now ‘possesses’ in all cases the capacity, if not to swim, at least to roll over and float until help arrives.

**Don’t bet a child’s life on drownproofing**. I pose the question: What is wrong with the above scenario? I hope that most readers are yelling ‘A LOT! Where is the parent supervision? Where are the multiple barriers?’ I believe, however, that much more importantly we should be challenging the basic presumption by infant ‘drownproofing’ advocates and parents that all or most children uniformly acquire and then perform this proposed ‘water proofing’ competence. If we consider the systems approach from earlier in this paper, it should be apparent that virtually any change in the young child’s characteristics such as his body composition as well as the mass of his pajamas and diapers, the angle at which he plunges in, the characteristics of the pool edge, water temperature, or even toys he might be holding all can interact in somewhat unpredictable ways to make the ‘taught’ behavior anything but repeatable under varying conditions. Would anyone want to bet their baby’s life on a mistaken notion that the rolling over and floating ‘ability’ is permanently possessed by the child?!

**Water competence and strong inference**

The arbitrary definitions of ‘swimming skill’ or water competence concern me due to the dynamic complexity of water environments and how individuals and their intended aquatic tasks interact. As discussed throughout this paper, water competence is complex and potentially fleeting under different situations and environmental conditions. We simply cannot accept that anyone who ‘possesses’ swimming skill demonstrated under relatively ideal conditions will transfer to other less ideal situations. This huge leap of faith represents a misunderstanding of how water competence arises from constraints. As I argued back in 1995 in *Aquatic Readiness*, I still believe that water competence ought to connote a broader set of skills than simply ‘being able to swim strokes’. Dynamic systems theory predicts that repeated and varied experiences performing a wide variety of
aquatic tasks under multiple water conditions will be a superior way to be water competent in many different situations.

Obviously along with a clearer definition we need to conduct lines of inquiry that explore the degree to which either ‘being able to swim’ or demonstrating ‘water competence’ will prevent drowning as well as optimal swimming performance. A classic article published 50 years ago in *Science*, Platt’s (1964) proposed that when confronted with a problem plagued by complexity such as acquiring water competence or preventing drowning, ‘strong inference’ principles provide the basis for rapid scientific progress. Specifically, Platt proposed that the best science 1) clearly states multiple alternative hypotheses; 2) designs studies to disconfirm one or more of the alternatives; 3) carries out the experiments cleanly; and 4) repeats the process. As with molecular biology and high energy physics, the complex questions associated with drowning prevention and water competence are ideally suited for a strong inference approach.

**References**


Biomechanics—interpretation and implementation

Bill Sweetenham
Business and sports consultant

“NEURAL AND SENSORY APPLICATIONS OF INTERVENTION IN IMPROVING TECHNIQUE AT HIGH SPEED AND RACE PACE”

XIIIth INTERNATIONAL SYMPOSIUM ON BIOMECHANICS AND MEDICINE
CANBERRA, APRIL 2014

PRESENTERS

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Jodi Cossor – Biomechanist, High Performance Sport New Zealand

Taisuke Kinugasa, Ph.D. – Senior Sports Physiologist, Japan Sports Council

Tom Vandenbogaerde – Senior Exercise Physiologist, High Performance Swimming
New Zealand

Dean Benton – Strength & Conditioning Consultant
"Neural and Sensory Applications of Intervention in Improving Technique at High Speed and Race Pace"

The question is –

How can technique and efficiency be improved and sustained at race speed and race pace swimming after 4 years or more of inefficient technique and motor pathway/muscle memory practice?

Quotes of influence which indicate the purpose of the contents of this presentation.

"The vast majority of athletes and swimmers can be trained to be good to great endurance athletes and swimmers, however only a very small few are born to be sprinters and/or breaststrokers"

... Bill Sweetenham

(EXPLANATION) –

Unfortunately a significant percentage of these endurance athletes and swimmers (based on flawed capability and capacity) desire and dream to be sprint or speed athletes and swimmers. This is in contrast to nearly all speed and sprint people who have absolutely no desire, aspiration or inspiration to be endurance athletes and swimmers. This separation is a winning point of difference in swimming for China and the USA where there remains a real focus on 200m up and 1500/800m down swimming, in addition to the speed programmes. Both these countries have coaches, athletes and programmes pursuing success in these events with real intent focused on the Olympic podium.

THE CONFLICT AND CONFUSION OF HAVING ENDURANCE ATHLETES FOCUSED ON SPEED EVENTS CHALLENGES ACCURATE TECHNIQUE DEVELOPMENT. COMPROMISED TECHNIQUE DEVELOPMENT IS RESPONSIBLE FOR LIMITING MANY SENIOR ATHLETES IN ACHIEVING THEIR OPTIMAL PERFORMANCE.

"Anyone can become a marathon runner; but you are born a sprinter"

... Article from Mercedes Benz Magazine 01-2014
Step 1

20% of race distance (20 metres)

*The 20% referred to here is based on the 100m event and would be applied proportionately for longer or shorter events.

Station 1

X1 Push
Or
X2

1 Push

1 Dive

Record time and number of strokes along with number of breaths - all at goal pace/speed.

Step 2

30% (30 metres)

20% (20 metres)

*The 20% and 30% distances are achievable, given that the athlete is utilizing a new and improved technique.

Station 2

X1 Push
Or
X2

1 Push

1 Dive

Record speed and number of strokes along with breathing pattern. The progression of speed will advance from previous best time to goal speed and goal protocols with exact precision.

Add push 20 + dive 30 = dive 50
Add push 30 + dive 20 = dive 50
Measure difference in speed and goal protocols.


**Station 3** — underwater dolphin kick at optimal speed X1 or X2

- Spiral dolphin kick: where the athlete executes a dolphin kick on their front, to the side, on their back, and then on the opposite side, and then on their front.

- Measure 10 metre speed and 15 metre speed and record number of spirals to the opposite edge of pool, plus speed (i.e., total time).

- Count number of kicks.

**Step 4**

- Video monitor combinations/singles —
  - Best performance
  - User technique improved image
  - Mirror (self)
  - 2-3 sets of up to 3 exercises of 2-3 repeats
  - Foot pulleys technique modelling “mirror”
  - Call room replay
  - Best major venue
  - Skills
  - Motivational

Using statistical analysis and observation, the staff (exercise physiologist, biomechanist, strength coach) will identify flawed technique due to changes in strength and mobility.

This has the potential to inhibit change and the staff should re-direct the athlete to the required treatment in order to address the improved skills and technique so that injury does not occur.

- Technique modelling (improved motor pathway)
- Improved technique
- Warm up muscles in preference to energy systems
- Muscle recruitment
- Activation for improved technique
- Improved muscle memory
Video monitor recording desired technical performance:
- Muscle recruitment
- Improved technique and modeling
- Muscle preparation for speed and movement
- Aggressive activation

Development:
- 40% to 50% to 60%
- 45% to 50% to 65%

Video monitor recording actual technical performance:

Record 50m — 50% time and protocols.

Compare 10m and 15m speeds and number of underwater dolphin kicks from Station 5 to the same values in Station 3.

The video (i-pad, GoPro, camera) should have recorded technique and skill improvements from Station 1 and 2 to Station 6. This should now be reviewed and comparisons (improvements) reviewed in detail by Coach, Biomechanist, Exercise Physiologist and Strength & Conditioning coaching personnel.

Add dive 50m (50%) to 30m (30%) and 20m (20%) for FES and efficiency of 50% of race distance at 100% of goal speed.

Video monitor

Step 6

Kick

Station 5

Video monitor

Choose OIR 1 of each either Kick X1 or Pull X1:
- Kick race time and measure distance
- Kick 50% of race distance (measure time plus %)
- Resistance pull race time (videoed) and measure distance
- Resistant pull 50% of race distance (measure time plus %)
NOTES

This can be repeated 4 times commencing with any step and building on a weekly basis. 4 times in the most appropriate and measured combination or single application. The stations may be varied in terms of commencing each practice. There is evidence that the greatest advantage and improvement gained is when athletes commence the set at Station No. 4.

1. Distance (measure speed and number of strokes) i.e. speed efficiency index = time plus stroke count.
2. Speed – Time (measure distance and number of strokes) either as achieved in 1. or according to goal time/speed or previous best time/speed.
3. Number of strokes (measure distance and speed/time).
4. Combination of ALL of the above.

ADDITIONAL SUPPORTING INFORMATION:
5. Stroke rate (model) to failure (utilising the above).
6. Optimal speed to failure (measure distance and time).

All of the above must be measured and recorded utilising "the improved technique" only.

NOTES - Distance and Percentage Charts

<table>
<thead>
<tr>
<th>Percentage</th>
<th>10m</th>
<th>20m</th>
<th>50m</th>
<th>100m</th>
<th>200m</th>
<th>400m</th>
<th>800m</th>
<th>1500m/Open Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>80</td>
<td>120</td>
<td>240</td>
<td>480</td>
<td>960</td>
</tr>
<tr>
<td>30%</td>
<td>15</td>
<td>30</td>
<td>60</td>
<td>120</td>
<td>240</td>
<td>480</td>
<td>960</td>
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</tr>
<tr>
<td>40%</td>
<td>20</td>
<td>40</td>
<td>80</td>
<td>160</td>
<td>320</td>
<td>640</td>
<td>1280</td>
<td></td>
</tr>
<tr>
<td>60%</td>
<td>30</td>
<td>60</td>
<td>120</td>
<td>240</td>
<td>480</td>
<td>960</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Recommended No. of repeats based on X times race distance

4-5
3-6
3
3
3
3
Using combinations of above percentages for the multi-event athlete:

<table>
<thead>
<tr>
<th>Time (m)</th>
<th>100-200m</th>
<th>200-400m</th>
<th>400-800/1500m</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-4</td>
<td></td>
<td></td>
<td>2-4</td>
</tr>
<tr>
<td>No. of repeats</td>
<td>1</td>
<td>1</td>
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Time = stroke count is often used as a measure, however, “time” is a continuous variable and “stroke count” is a discrete variable. “Speed” (or more accurately – velocity - m/second) is a function of distance and time. Therefore efficiency is the ability to maintain velocity (i.e. with minimal variation) throughout the required distance. Swimming efficiency is therefore related to energy expenditure and the way this is converted to mechanical application of power. As this process does not measure energy, caution must be exercised on how “efficiency” is defined.

Stroke rate (and therefore stroke count) provides the athlete and staff with an indication of mechanical efficiency. The goal is to swim fast (i.e. greater m/second) at an economical stroke rate.

This concept has been practised for 4 weeks (4 exposures) using it once per week followed by 2 weeks with only 1-2 exposures per week. Then repeated for a further 4 weeks at once per week, but with the process focused on where the individual responded best to the application of the new technique and skill in the first block of 4 weeks.

Athletes in groups could commence the rehearsal practice by commencing each set at each (but different) station. It is possible and practical to commence the same station in each training exposure.

It could look like this (example of a 12-16 week cycle):

- 2 weeks at 1 exposure to 2 applications, usually 1 distance.
- 4 weeks at 4 exposures to all 4 concepts with varying commencement points i.e. (example only) –
  - Week 1 | 3-2-1-4
  - Week 2 | 2-1-3-4
  - Week 3 | 4-3-2-1
  - Week 4 | 1-2-3-4

- 2 weeks repeat from the first 2 weeks
- 4-5 weeks as above but drop 1 weak series each week (race preparation).
- Sequentially download with improved performance.
- 2 weeks repeat from the first 2 weeks

- 4-5 weeks as above but drop 1 week series each week (race preparation)

- Sequentially download with improved performance.

- Rest/recovery in each set is based on the need of the individual. Enough rest for the practice protocols not to reflect compromise due to inadequate rest and with as little rest as possible to achieve the targeted outcome.

- Measure rest with 20-40 breaths in preference to a time-governed interval. Focus the athlete on exhaling.

With progression 4, the 60% repeat can be built up from 40% to 50% and finally 60%. However this would cease where the improved and modified technique broke down.

The 60% could also be achieved by a progression of 45% to 50% to 60% of race distances at 100% of first personal best pace/speed, then accurate conversion into goal pace/speed where efficiency is maintained or improved.

The percentages all relate to percentage of race distance at 100% of previous best speed converting into goal speed as early as possible in the practice and rehearsal process.

Given that the majority of athletes compete in at least two distances, the stations can be manipulated to address this need, both within a station or by set up to many event specifics.

As an example, the 20% and 30% can be completed at 50 metre distances and the 60% at 100 metre distances. Also the practice sets may take an odds and evens approach with varied sets focusing on speed development (50 metre event) and other sets focusing on the longer events (100 or 200 metres).

In this case, both speeds and distances would change and vary to suit the needs of the individual and the event, ie. in Sets 1 and 2 the focus might be on the 100m event and in Sets 3 and 4 focusing on the 200m event. The mixture of 400-200 distances is also possible.
With advanced preparation in the process of performance to perfection, the athlete might do a series of 6 repeats (instead of 4) with the 5th set being “soft” in effort but high in skill and technique demand. This would usually occur in the second series of 4 repeats.

The longer the target distance, then the fewer repeats. However, the demand for both improved technique and speed does not change, and must not be compromised.

The new improved technique required must be made clear to the athlete well before the process of performance to perfection commences.

Supporting practice sets once improved technique is achieved and confirmed are (based on improved protocols):

A) 16-20 repeats of (sustaining improved skill and technique):
   1) 25% of race distance at 100% of previous best time converted over time to goal protocols (distance – speed – number of strokes – stroke rates)
   2) As above with 30% of race distance at 100% of previous time converted over time to goal protocols (distance – speed – number of repeats – stroke rates)

A shared concept with New Zealand canoe coach and coach of world champion canoe athletes – Coach Gordon Walker.

B) A one-off test repeat of – 125% of race distance at 100% of previous best pace to goal pace
   1) +15%; 2) +12%; 3) +10%; 4) +8% possible for some athletes; 5) +6-4%

The athlete must hold improved technique and skill. Stop wherever improved technique breaks down.

C) 10x30 or 12x30 (reduce by 1 second per 50m from goal pace +10 seconds or +12 seconds at minimum/maximum values, holding improved technique – must be monitored to identify technical failure. Minimum number of improved technique strokes plus appropriate speed reduction of 1 second per 50m.
CONCLUSION

It is well accepted by experienced coaches that it is possible to add speed and fitness to efficiency, but rarely can the reverse be put in place. This model or concept, when accurately applied to enhanced individual efficiency even after more than 4 years of 12 hours per week of incorrect motor pathway and muscle memory will improve technique and skills at the senior level.

However, this concept may not improve technique at slower speeds. Coaches and athletes have battled against trying to significantly improve technique at speeds slower than race pace/speed only to find at higher speeds and under fatigue and pressure that they revert back to the original and inefficient technique and speed efficiency that were in place prior to the improvements made at slower speeds.

The identification of aggressive “racing” competitive talent often goes hand in hand with repeated technique and skill breakdown. The concept included within this presentation has the potential to combat and defeat this when applied with clinical precision.

I have applied this concept successfully to numerous international podium athletes over a 15 year period.
2 Biomechanics

The velocity and fatigue index of various leg kicks in rescue towing

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Keywords: rescue, leg kicks, velocity, fatigue

Introduction

A drowning episode can occur under many different conditions and unfold in many variable ways (1). The condition (active, passive, unconscious, etc.) and size of the victim, the distance from safety (shore, pool deck, pier, etc), the water conditions (waves, temperature, currents, visibility, wind, etc), the experience, knowledge, skill and fitness of the rescuer, availability of rescue equipment, and other variables, make a swimming rescue a very dangerous enterprise indeed. In fact, a growing number of agencies have removed direct contact swimming rescues from their programs of teaching lifesaving to the general public (possible future bystanders) and relegated them to the training of professional lifeguards (2). Possible future bystanders are thus trained to use only swimming rescue towing techniques involving equipment—either specifically designed rescue equipment or more likely, randomly available objects at hand. The motive of course, is to increase the distance between the rescuer and victim, avoiding direct physical contact.

The optimal situation in rescue towing is for the rescuer to be versatile enough to be able to select the most appropriate technique relative to the variables named above. This allows the rescuer to make choices but it also demands a broad spectrum of rescue skills. The inexperienced and less versatile rescuer may have no choice except to attempt the rescue or not to attempt the rescue. The need to use perhaps the only technique which this rescuer has mastered, though inappropriate, may jeopardise the rescue and reduce the chances of success. The needs in real rescue, as described here, are many and varied, and usually unpredictable. Appropriate training of the general public includes a variety of techniques and the concomitant knowledge to use them, allowing the rescuer some choice, according to the conditions.

Lifesaving competition also involves a variety of techniques. Well over a century old, this form of competition has a history of attempting to simulate real rescue situations. As competition has developed, and among other things, has also created an indoor variation, the competition has become more formal. Complex rules have been established (attempting both fair competition and simulated real rescue). The rules of each event are sufficiently rigid to not allow much choice to the rescuer. The distance is fixed, whether or not fins are to be used, whether or not the simulated victim (mannequin) is submerged, whether a rescue device is to be used, and more, are both specified and known in advance (3). We see immediately that the needs of real rescue and competition rescue are not quite the same (4). They have, however, so much in common that research can help us better understand both. Research will also help us identify both similarities and differences between real rescue and simulated rescue in competition. Given that only a few studies have been conducted on rescue towing there is urgent need for further research (2).

Several studies have compared towing with the flutter and dolphin kicks, with and without fins (5,6,7,8). Some have compared different types of fins (9). Still others have examined towing, including both arm and leg strokes (10,11,12,13,14). While performance with fins has been shown to be superior, the most common situation in real rescue is that fins are not available, and also in
competition, some events are specified to be performed without fins. To the best of our knowledge, no study has yet compared the scissors kick to other kicks using the legs only without fins, and while performed in the side lying position.

**Methods**

With the body position of the rescuer (side lying) and the victim (supine lying) held constant, the velocity developed over 25m without fins, was examined. A standard ILS rescue mannequin was used with the grip on the back of the neck. The lead arm was extended and passive. A speedometer attached to the mannequin was used to determine velocity. The fatigue index (FI) was also obtained. The leg strokes examined were the breaststroke, scissors, flutter and dolphin kicks, in a random order design. Eleven experienced lifeguards served as subjects. A fifteen minute rest period was held between trials. All trials were also video recorded under water. Only subjects who completed all four trials were included in the analysis.

![Figure 1](image1.png) The trial layout

Age, gender, height and weight were also recorded.

![Figure 2](image2.png) The speedometer  
![Figure 3](image3.png) Instantaneous velocity – time curve

Figures 2 and 3 show the speedometer and a printout of the time – velocity curve. Note the noise created by the speedometer being attached to the mannequin rather than the rescuer.

The fatigue index was calculated using the formula:

\[
FI = \frac{\bar{x}_{iv} - \bar{x}_{fv}}{\bar{x}_{iv}}
\]  

(Eq. 1)

where FI is fatigue index, iv is initial velocity and fv is final velocity
Defining the initial and final velocities in different ways, four different calculations were made. These were based on: a) the mean velocity of the first one half of the 25 m swim vs the mean velocity of the second one half, b) the mean velocity in the first two seconds vs the mean velocity in the last two seconds, c) the highest instantaneous velocity vs the lowest, and d) the slope of the linear regression. Further research will possibly identify one of these as most appropriate.

**Results**

Age, gender, height and weight were examined. None of these demonstrated a relationship to the dependent variables of velocity and fatigue index. Visual inspection of the curves below, as well as the calculated FI itself, indicate a more rapid degeneration in the velocity for the crawl and dolphin kicks (Fig. 4). Normalising all curves so that the start velocity was the same (Fig. 5) reveals a steeper downward slope for crawl and dolphin kicks.

![Figure 4](image1.png) **Collective curves for all subjects for each experimental kick**

![Figure 5](image2.png) **Normalised curves**

Figure 6 shows an example of the Fatigue Index calculated by splitting each trial in half and the statistics associated. The box plot chart depicted shows, for each of the swimming techniques, the
median fatigue index – black horizontal bar, the inter-quartile range – the inner 50% of the fatigue indexes, represented by the coloured boxes, and the maximum and minimum fatigue index, represented by the whiskers.

**Anova repeated measures:**

<table>
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<th>Mean Sq</th>
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<td>33.5</td>
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</tr>
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</table>

**Pairwise comparisons using paired t-tests**

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<th>D</th>
<th>FC</th>
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</thead>
<tbody>
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<td>Sc</td>
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</table>

Figure 6  A sample box plot of the calculation of FI

**Density distribution of speeds**

![Density Distribution of Speeds](image)

**Figure 7**  Density of velocity values

For all of the methods of calculating FI, the breaststroke kick consistently resulted in the lowest FI and the dolphin kick the highest in three of the four, exceeded only by the crawl kick in one calculation.

Fig. 7 shows the density of velocity values, i.e. the frequency of the occurrence of specific velocity values for each leg stroke. Simply put, the higher the density, the longer participants were found swimming at the corresponding velocity. The key in Fig. 7 shows the average time for all trials for each
stroke. Each line represents the density curve for one stroke (using data from all subjects). Fig. 7 indicates that: a) breaststroke attained the highest velocities for longer time, b) scissors kick never reached velocities as high as breaststroke but its top velocity was sustained for longer; c) front crawl and dolphin kicks spent most of their time at a velocity considerably lower than their top velocity (0.4 vs. 0.8).

Discussion and conclusions

There were several limitations suggesting that these results should be taken with caution. These were, a) most subjects failed to perform a maximum effort while towing the mannequin thus reducing the accuracy of the velocity curves, b) the subjects were less familiar with the scissors kick and thus less skilful, thereby affecting the comparison with other kicks, c) both a and b reduce the accuracy of the calculated FI, d) some subjects failed to maintain the side lying position when using the breaststroke kick, and finally, e) the subjects were tested over a rescue distance of only 25 m.

The aim of holding the body position of the rescuer constant in a side lying position was to fairly compare the leg kicks studied as well as to use what most experts consider the optimal body position. The side lying position offers a) an effective position in which to use the free arm, b) ease of breathing for the rescuer, c) the possibility of constantly keeping visual contact with the victim as well as maintaining a line of site with the target haven of safety. Of course, under some conditions the supine position of the rescuer might be optimal and will be the subject of further study.

Despite the above limitations, general indications seem to be clear. The scissors and breaststroke kicks clearly outperformed the dolphin and crawl kicks in rescue towing as performed here. These differences were statistically significant. The breaststroke and scissors kicks performed almost equally well, with slight advantages to the breaststroke kick. The breaststroke kick consistently gave the highest velocities and the lowest FI values. The dolphin kick gave consistently the lowest velocities and the highest FI. But, since fatigue alone doesn’t reveal the whole picture, we did take a look at how well each stroke ‘performed’ in terms of speed. Ultimately, a swimming technique with high velocity decay may still be preferred if it results in shorter rescue time than the remaining techniques. In order to evaluate this we took a look at how fast participants were going throughout each trial. This can be seen in Figure 7, which shows how frequently a velocity was measured during trials in each of the 4 strokes. This chart, together with the box plots that showed breaststroke and scissors kicks to be the least tiring techniques, allow us to further emphasise these 2 kicks as the most efficient because they both attained and sustained higher velocities.

In summary, we’ve found statistically significant performance differences between strokes, with the breaststroke and scissors kicks being the most efficient techniques in rescue towing without fins, providing the highest velocities while keeping fatigue at a minimum.

References

The effect of pullout timing on breaststroke turn performance

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Keywords: breaststroke, turns, swimming, performance analysis

Introduction

In swimming races, between 20 and 40% of the total event time is spent turning (Thayer & Hay 1984; Blanksby et al. 1998). Therefore turns are an important consideration for performance because an improvement in turning technique could improve event time and placing. Of the four competitive swimming strokes, breaststroke turn times are the slowest and most variable, and Newble (1982) suggested that this was likely a result of the greater technical expertise required. Breaststroke turns also involve longer breakout distances and breakout times compared with the other strokes (Chow et al. 1984).

According to the international swimming federation rules for breaststroke, ‘After each turn, the swimmer may take one arm stroke completely back to the legs during which the swimmer may be submerged. A single butterfly kick is permitted during the first arm stroke, followed by a breaststroke kick. The head must break the surface of the water before the hands turn inward at the widest part of the second stroke’ (FINA 2012, p. 167). The timing and execution of these aspects of the turn could all affect the final race time.

During a breaststroke turn, swimmers push off the wall with both feet which allows them to travel at a higher velocity than they can actually swim the breaststroke. Following the push-off, they adopt their most streamlined position to minimise their drag and rate of deceleration, and thus maintain this higher velocity for as long as possible. Theoretically, the optimal breaststroke pullout is one in
which the swimmer maximises the amount of time they travel above the velocity at which they can
swim, and minimises the time spent below the velocity at which they can swim breaststroke. This is
because if they travel for too long below their average free-swimming velocity, it would be faster for
them to be actually swimming. The aim of this study was to determine the effect of the timing of the
breaststroke pullout on overall turn performance.

**Method**

Five Scottish national-level swimmers (specialist breaststrokers) each performed eight breaststroke
turns, four using their ‘normal’ pullout technique, and four using an ‘early’ pullout where athletes
were instructed to spend less time in the initial glide phase and less time at the end of the pullout
before the start of the recovery. Trials were recorded using above- (50 Hz) and under-water (25 Hz)
video cameras situated perpendicular to the plane of motion and calibrated for 2D kinematic analysis.
The above-water camera was used to measure breakout time, breakout distance and the overall
performance outcome which was the time from the wall to 13 m (this was the maximum distance
available within the field of view).

The swimmer’s left hip was digitised from the point the feet left the wall to the point of breakout
using the under-water camera view in SiliconCoach Ltd (Dunedin, New Zealand). Data were filtered
with a dual low-pass 4th order Butterworth filter at a frequency of 2 Hz based on the results of a
frequency analysis. The initial velocity off the wall was measured from the first frame the swimmer’s
feet had left the wall to two frames afterwards. This was used to determine whether the swimmers
pushed off the wall with a similar velocity for both conditions and therefore any differences evident in
the time taken could be attributed to the timing of the pullout. Graphical representations of the
swimmer’s underwater velocity from the wall to the point of breakout were used to determine how
the different pullout methods affected the underwater performance.

Each swimmer’s average free-swimming velocity was taken from race analysis data collected at the
most recent major championships they had competed in, and is calculated as distance travelled
divided by time taken during the free-swimming part of a race (i.e. excluding any portions of the race
influenced by starts or turns). This was used to assess the velocity during the pullout phase relative to
the average velocity at which they can swim. The time spent above and below the average free-
swimming velocity was calculated as a percentage of the overall time taken from leaving the wall to
the breakout, and compared between the normal and early pullout conditions. Variables for the
normal and early pullouts were compared with a paired t-test and the level of statistical significance
was set at $p < 0.05$.

**Results**

The early pullout significantly improved the time taken to reach 13 m ($p < 0.01$). The early pullout was
on average 0.3 s faster than the normal pullout with the range of individual improvements being
between 0.12 and 0.6 s. The early pullout also resulted in a significantly shorter breakout distance and
time compared with the normal pullout ($p < 0.01$). There was no significant difference in the initial
velocity off the wall (Table 1).

| Table 1 | Comparison of variables measured for the normal and early pullout conditions |
|---------|-----------------------------|-----------------------------|
|         | Normal pullout | Early pullout  |
| Time to 13 m (s) | 8.38 | 8.08* |
| Breakout time (s) | 5.88 | 4.27* |
| Breakout distance (m) | 9.39 | 7.41* |
| Initial velocity off wall (m.s$^{-1}$) | 2.52 | 2.54 |

* denotes a significant difference between the normal and early pullouts ($p < 0.01$).

In the normal pullout, an average of 51% of the underwater phase was spent travelling below the
mean free-swimming velocity. In the early pullout, the time spent below the mean free-swimming
velocity was significantly \((p = 0.046)\) less at 39%. The reduction in time spent below the average free-swimming velocity during the early pullout can be observed in the swimmers’ velocity profiles (Figures 1 and 2).

In the normal pullout, the swimmer started to pull when they had decelerated to 1.35 m.s\(^{-1}\). During the early pullout, they started to pull when travelling at 1.55 m.s\(^{-1}\) which was closer to their average free-swimming velocity, as taken from race analysis. In the second deceleration phase, the swimmer travelled below their average swim velocity for less time compared with their normal pullout.

**Figure 1**  Example comparison of velocity profiles for the normal and early pullout for Swimmer 1

In the normal pullout, the swimmer started the pullout when they reached a velocity comparable with their free-swimming velocity. During the early pullout, they started to pull before they reached their free-swimming velocity. In the second deceleration phase, the swimmer travelled below their average swim velocity for less time compared with their normal pullout.

**Figure 2**  Example comparison of velocity profiles for the normal and early pullout for Swimmer 2

**Discussion**

The aim of this study was to determine the effect of the timing of the breaststroke pullout on overall turn performance. For the five swimmers who participated in this study, the earlier pullout significantly improved the time taken to reach 13 m by an average of 0.3 s. The early pullout also
significantly reduced the breakout distance and breakout time. There was no difference in the initial velocity off the wall and therefore the improved performance and difference in the breakout can be attributed to the different timings of the pullout.

Analysis of the velocity from the point of leaving the wall to the point of breakout revealed that each swimmer spent less time travelling below their average free-swimming velocity before the breakout when using the earlier pullout. The velocity profiles also showed that the optimal timing of the pullout was very individual as it is dependent on the time taken to reach their average free-swimming velocity following the glide off the wall. This in turn is based on the individual’s initial velocity off the wall, their rate of deceleration and the average velocity at which they can swim breaststroke.

Although all swimmers in this study improved their time to 13 m using an early pullout, the velocity profiles indicated that the timing of the early pullout was still not theoretically optimal and there could be room for further improvements. For example, Swimmer 2 (Figure 2) improved their time to 13 m by an average of 0.4 s using the earlier pullout, however Figure 2 shows that the initial pull in the early pullout condition was in fact too early as they had not yet reached their average free-swimming velocity. This swimmer could have held the streamlined glide position longer, as they did in their normal pullout. This maximises the underwater phase performance and, as an added advantage, conserves energy in doing so. Therefore, for Swimmer 2, a combination of their normal pullout for the first deceleration phase, and the early pullout for the second deceleration phase could be the most effective timing.

The findings of this study appear to contradict previous studies which have found that the swimmers with better breaststroke turns travel a further distance underwater (Chow et al. 1984; Blanksby et al. 1998; Mason & Cossor 2001). This could be because the swimmers in the current study are of a lower skill level and have not yet achieved optimal pullout timing in order to maximise the underwater phase of their turn performance. The study by Mason & Cossor (2001) investigated Olympic finalists and semi-finalists and it is possible that these more elite Olympic swimmers did perform the pullout with optimal timing but due to them having a higher initial velocity off the wall and a better streamline position, this would result in them travelling a longer time and distance before reaching their free-swimming speed. To lengthen the breakout time and distance requires an increase in the initial velocity off the wall and/or a decrease in the rate at which velocity is lost during the glide phases.

This study has shown that the timing of the breaststroke pullout can significantly affect turn performance and therefore coaches and athletes should consider this as an area for potential improvements. When practising the breaststroke turn, attention should be paid to the timing of the different aspects of the pullout as well as the technical execution of the skills. However, consideration should also be given to how a change in the pullout timing may affect other parts of the race. For example, an earlier pullout reduces the breakout distance and time, and therefore swimmers would need to start swimming earlier and take more strokes per lap which may have physiological implications in a race.

Conclusion

The findings of this study showed that the timing of the pullout in a breaststroke turn can significantly affect the turn time. Coaches and athletes should therefore consider and practise the timing of the breaststroke pullout as well as the technical execution of the skill in order to maximise the underwater phase of the turn. The optimal timing of the pullout is dependent on the individual athlete’s velocity off the wall, the rate at which they decelerate and their average free-swimming velocity. Furthermore, because a swimmer’s velocity off the wall, rate of deceleration and free-swimming velocity will change over time, the optimal timing of the pullout will also change and this should therefore be monitored regularly.
References


Effect of sculling propulsion on body kinematics in displacement

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Keywords: quasi-steady, lift, drag, velocity, acceleration

Introduction

Swimming propulsion and its effect on body kinematics (displacement, velocity and acceleration) have been studied in different swimming phases (such as pull and push in freestyle) and the resultant changes in the swimmer’s body velocity (CM or hip).

Sculling is a basic propulsive action with four hand movements: outsweep, supination, insweep and pronation. 3D analysis showed a zigzag path, where hand displacement is mostly forward, with strong hand rotations during the change of direction (Arellano 2011). The in-depth study of this propulsive action includes kinematics of the hand, flow visualisation and PIV in the typical situations: hovering and displacement (Arellano & Pardillo 2007). To understand the full effect of propulsion – quasi-steady and unsteady (Arellano et al. 2006) we can measure the body displacement produced and its acceleration. This can provide a link between propulsive mechanisms and their effect on the body in a basic and experimentally controlled sculling action, easier to perform than full stroke propulsion.

Considering the full body static during the performance of trials (as can be seen in Figure 1), body drag can be obtained, in a similar situation to previous studies on gliding, body drag after the second gliding position of the breaststroke underwater stroke applying inverse dynamics (Vilas-Boas et al. 2010). It is possible to calculate the resultant force applying the equation P-D=ma (Vogel 1994), knowing body acceleration and mass.

The aim of the study was to know the effect of sculling propulsion on body kinematics in displacement and hence the resulting force in each propulsive phase of the sculling action.

Method

A sample of 25 healthy collegiate students volunteered to participate in this study (12 males, age=22±1 years, height=177.4±5.8 cm, mass=70.8±9.2 kg; 13 females, age=22±2 years, height=169.5±5.2 cm, mass=60.7±4.5 kg). Written informed consent was obtained from each participant prior to implementing the study, which was approved by the university’s Ethics Commission. Each participant performed a 20m trial using normal sculling (arms and elbows fixed close to the water surface making an angular displacement of forearm and hand). A linear encoder tethered to the
swimmer’s belt allowed intra-cyclic speed recordings (200 Hz) synchronised with a bottom view video camera PAL 50Hz (see figure 1) and four HD (60Hz) cameras that allowed a detailed analysis of the sculling phases. An intermittent flashing underwater light enabled us to synchronise the five cameras. The instantaneous and average hip speed (V) and acceleration (A) were obtained during no less than six sculling cycles. All the sculling phases were identified from video observation. A Butterworth filter with a cut-off frequency of 6Hz was applied (Eser 2007). A first derivate with first-order central differences was applied to calculate the acceleration. The hip velocity recordings were normalised defining each cycle as 100%. The duration of each phase was expressed as a percentage of the sculling cycle. Mean and SD values of velocity and acceleration were obtained for each phase and averaged for each swimmer during six cycles. Sculling rate was calculated using the number of cycles recorded divided by the total duration in seconds (SR—Hz) and sculling length (SL—m/cycle) was obtained by dividing the mean hip velocity of cycles recorded by mean sculling rate.

A linear encoder records the hip velocity (200Hz) synchronised with a video camera (50Hz). Both signals are processed by an AD converter and sent to the computer through two USB ports.

Figure 1 Experimental set-up

For the assessment of intra-cyclic velocity variation (IVV), the coefficient of variation of the average of 6 hip velocity normalised sculling cycles was calculated using (SD/Mean*100) (Marques-Aleixo et al. 2013). This variable helps the relative variability of trial or subject records to be understood. Mean and SD or confidence interval (CI) values of the percentage duration, velocity and acceleration during each sculling phase: outsweep, supination, insweep and pronation was calculated.

The fixed and horizontal position of the body allowed the calculation of total Drag (D=m·a) using inverse dynamics, without considering added mass effect (Vilas-Boas et al. 2010). In the present study, the resultant force was the difference between arm propulsion and drag and it was calculated as: P-D=m·a, without considering added mass effect. Thus the resultant force is positive when the swimmer is accelerating due to the propulsive force and negative when the drag is higher than arm propulsion. An analysis of this resultant force related to the sculling phases will be performed.

Statistics: Means and standard deviation or interval of confidence has been calculated for each variable and each percentage after normalising the variable versus time. These results are presented in figures 2, 3, and 5. One-way repeated measures ANOVA has been performed to find the differences in percentage of phase’s duration. Sphericity was tested applying the Mauchly’s test. If data violates the sphericity assumption, a specific correction was applied to produce a valid F-ratio. Bonferroni post hoc test was applied to compare the four phases averages.
**Results**

The average values were: \( V = 0.47 \pm 0.09 \text{ m/s}, \ SR = 1.36 \pm 0.19 \text{ Hz} \) and \( SL = 0.35 \pm 0.08 \text{ m/cyc} \), with acceleration obtaining values close to zero. A sequentially and small variation of \( V \) was found with an IVV=2.84% and a range of 0.05 m/s (see Figure 2), while the acceleration showed higher variations, with a clear peak at the end of the insweep phase (see Figure 3) and a minimum value of -0.32 m/s\(^2\), a maximal value of 0.37 m/s\(^2\) and a range of 0.69 m/s\(^2\). The analysis of the duration of the phases showed similar percentages of the total sculling cycle for outsweep and insweep phases (about 32% each phase) and the pronation and supination phases (about 18% each phase). The hand displacement phases were two times longer than the rotation phases.

![Figure 2](image)

**Figure 2**  Normalised total group mean (±SD) hip velocity values with the four phases of the sculling cycle (n=25).

![Figure 3](image)

**Figure 3**  Normalised total group mean (±SD) hip acceleration values with the four phases of the sculling cycle (n=25).
A visual inspection of each individual normalised average record allowed two types of velocity paths to be defined: a) a near constant speed during the cycle and; b) not constant with velocity peaks.

In the second case IVV was higher than 8% and/or ranges higher than 0.1 m/s were found in ten out of 25 cases. Negative acceleration and positive peak values had much more variability in this second case with ranges of about 3 m/s².

Phase’s duration analysis one-way repeated measures ANOVA, showed statistical differences \[F(3,96) = 78.69 \ p<0.01\}. No statistical differences were found between inward and outward phases and between pronation and supination phases. Displacement phases were significantly longer than rotational phases (see figure 4).

The resultant force varied from -20.9 N to 24.4 N. Peak +A values were located during the second part of the insweep and outswep hand movements (more propulsion than drag) and peak -A after transitional rotating phases (less propulsion than drag), see Figure 5. This average force versus the phase graph of the cycle shows a clear peak at the end of the insweep phase. In participants with higher variability, peak resultant force values from -104 N to 97 N were obtained.
Discussion

The kinematic analysis of body displacement may provide some clues for understanding swimming propulsion. Therefore, in the present study, the velocity and acceleration of the body during a sculling motion were verified and the resultant force, the difference between propulsive forces and drag force, was estimated.

It was possible to note two kinds of behaviour by considering the participants: (1) body velocity was almost constant, thus the body’s acceleration was close to zero, indicating that the resultant force is almost constant as well and (2) body velocity varied, thus the body’s acceleration was different from zero, indicating that the resultant force was sometimes positive and sometimes negative. Moreover, on average, the body’s acceleration and resultant force presented a positive peak at the end of the insweep phase and at the beginning of the pronation phase, while negative peaks were noted between supination and insweep phases and between pronation and outsweep phases.

IVV is a good indicator of technical skill when applied to freestyle (Vilas-Boas et al. 2011). In this study less velocity variation is expected than in freestyle when the swimmer applies all the possible propulsive mechanisms (quasi-steady and unsteady). Values of IVV = 14% ± 4% were obtained in French swimmers (Seifert et al. 2010) or IVV = 29% ± 9% for swimmers with disabilities (Marques-Aleixo et al. 2013). Our results showed an IVV = 2.8% ± 0.4% with some extreme case of 11.7% ± 0.8%. Regardless of its simplicity some participants did not acquire the expected skill in the sculling task after eight weeks of specific training (2 sessions per week) or introduced some individual variations that resulted in higher IVV.

These results may be due to the participants, who have different experience of swimming. For instance, although kinematic variables such as hand velocity, acceleration and orientation were not calculated, they varied in a cycle of sculling motion according to other studies (Homma & Homma 2006; Arellano 2011). This means that some participants were able to control the hand movement and generated a constant resultant force (first case described), which may imply less wasted energy. This is a difficult task since unsteady mechanisms play an important role in sculling propulsion (Arellano et al. 2006; Matsuuchi et al. 2009). However, since there were some participants that were not able to control the hand movement efficiently, on average the resultant force was not constant. In order to know about the variable or variables that generated this difference, it is necessary to analyse the 3D hand kinematics, the next phase in this research project.

Conclusions

The values of resultant force obtained thanks to the application of inverse dynamics will be a reference for future measurements based on 3D hand kinematics (quasi-static approach), CFD simulations and PIV measurements.

All our previous study results and those obtained in this research suggest that a careful application of the sculling drills is necessary in order to obtain the desired effect on formal strokes and swimming propulsion. An inappropriate hand and forearm action results in an excessive intra-cycle velocity variation mostly due to outsweep and supination phases being performed incorrectly with very limited propulsive capabilities.

A more accurate analysis that combines the effects of 3D sculling hand path on body kinematics will provide clues to establish a set of specifically oriented sculling drills that will try to increase propulsion during the practice of the formal strokes.

References

The importance of sagittal kick symmetry for underwater dolphin kick performance

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Keywords: swimming, kinematics, downkick, upkick, performance, dolphin kick, underwater

Introduction
The underwater dolphin kick is a cyclic motion where the toes oscillate in a regular fashion with one spatial maximum (up-peak) and one spatial minimum (down-peak) in the vertical direction occurring over the course of one cycle. Underwater dolphin kick can be broken down into two phases; the downkick (DK) and upkick (UK). In a ventral body position, the DK is characterised by hip flexion and knee extension and occurs from the up-peak position and ends in the down-peak position; the UK is characterised by hip extension and knee flexion and occurs from the down-peak position and ends in the up-peak position. Kicking symmetry in the UDK is defined as the ability to produce equivalent propulsion during the DK and UK phases. This is accomplished through similar kinematics between the DK and UK phases. Theoretically, symmetry between DK and UK phases should result in more consistent centre of mass (CM) velocity as there are two equivalently propulsive phases, compared with one propulsive and one resistive phase in an asymmetrical kick cycle.
In swimming, vortices represent the transfer of momentum from water to body and vice versa, resulting in body acceleration (Ungerechts, Persyn & Colman 1999). Previous studies have demonstrated that efficient swimmers create a large static vortex at the end of the downward kick and a small vortex at the end of the upward kick, whereas inefficient swimmers create small translating vortices at the end of the downward kick and no vortices at the end of upward kick (Arellano 1999; Arellano et al. 2000).

Previous studies have compared the kinematics of human undulatory propulsion to the kinematics of dolphins/cetaceans (Ungerechts 1983; Von Loebbecke, Mittal, Fish & Mark 2009a; Von Loebbecke, Mittal, Fish & Mark 2009b). Ungerechts (1983) compared the kinematics of the butterfly stroke with dolphins and found that the primary difference between the human swimmers and dolphins was that dolphins were able to perform symmetrical DK and UK phases; in contrast, the human swimmers were relatively less effective at the UK phase, and he concluded that only swimmers who were able to hyperextend their knees would be able to perform the UK phase effectively. Von Loebbecke et al. (2009a, 2009b) compared the kinematics of the UDK in humans with odontocete cetaceans, finding that humans were less propulsively efficient and slower than cetaceans over the range of kicking frequencies and kicking amplitudes selected by the human swimmers. The differences between humans and cetaceans were attributed to the disadvantageous anatomy and musculature of humans, such as narrow feet and less-flexible joints, which especially limit the performance of the UK phase. Given their anatomical differences, symmetry between the DK and UK phases is an obvious limitation for human swimmers when compared with cetaceans; however, the relationship between kicking symmetry and performance has not been adequately studied in human swimmers.

The purposes of this study were to evaluate the kinematics of DK and UK phases and how symmetry between DK and UK is related to performance. Symmetry in this experiment was evaluated by comparing joint marker paths, joint angles, horizontal displacement of the CM, horizontal velocity of the CM, and vertical toe velocities during the DK and UK phases.

**Methods**

Fifteen adult male swimmers between the ages of 18 and 28 (21.5±3.2 years) with at least five years of competitive swimming experience (11.4 ± 5.6 years) ranging from the provincial to the international levels volunteered to participate in the study. Each swimmer was filmed performing three trials of maximum effort UDK over 15 m, at a constant depth (between 0.5 and 1.0 m) with at least three minutes of rest between trials. The swimmers were required to perform the trials in a ventral body position.

All trials were filmed from a Lorex CVC-6991 (Lorex Technology Inc., Ontario, Canada) underwater video camera (frame resolution = 720x480 pixels, frame rate = 30 Hz) and recorded to the hard drive of a digital camcorder (JVC GZMG555, JVC Kenwood Holdings, Japan). The underwater camera was secured 0.5 m below the surface of the water and 7.5 m from the initial impulse wall. The swimmers’ plane of motion was 4 m from the camera and perpendicular to the camera’s field of view. A 2 m reference line was submerged 0.5 m parallel to the water surface along the swimmers’ path of motion, recorded to the camera hard drive, and subsequently removed from the pool prior to the swim trials. Videos were cropped and then augmented with a photo of the reference line at the beginning of each video (Pinnacle Studio Version 9, Pinnacle Systems, California, USA). Edited videos were imported and digitised manually in HUman Movement ANalysis software (HMA Technology, Ontario, Canada). The two-dimensional biomechanical model chosen for kinematic analysis was based on the one proposed by de Leva (1996) using 12 anatomical landmarks on the right side only. All raw data were filtered using a Butterworth filter with cut-off frequencies from 4-5 Hz based on a residual analysis of the landmark data (Winter 1990). The central kick cycle was analyzed.

We define one complete dolphin kick cycle starting immediately following the up-peak position, followed by the DK phase that ends in the down-peak position, followed by the UK phase that ends in the up-peak position. All reported kinematic variables were determined for the whole kick cycle and
also for the DK and UK phases independently. Symmetry between the kinematics of the DK and UK were evaluated by dividing DK values by UK values, where ratios approaching one were considered to indicate symmetry between the DK and UK for that variable. Kinematic variables used for comparison were: normalised DK duration (\% DK) and UK duration (\% UK), horizontal kick displacement during DK (\(d_x_{DK}\)) and UK (\(d_x_{UK}\)), horizontal velocity of the CM during DK (\(V_x_{DK}\)) and UK (\(V_x_{UK}\)), and vertical velocity of the toe during DK (\(V_{zT,DK}\)) and UK (\(V_{zT,UK}\)). Joint angles were also calculated, and the maximum flexion and extension were determined for each kick cycle. To evaluate symmetry in joint angles between DK and UK, the ratio of maximum flexion/maximum extension was calculated for each joint.

For each subject, the trial with the highest average horizontal CM velocity (\(V_x\)) was chosen for between subject comparisons. Pearson product-moment correlation analyses were performed between \(V_x\) and DK and UK kinematic variables to determine how kinematics of each phase relates to performance, and between \(V_x\) and symmetry ratios to determine how kinematic symmetry between DK/UK relates to performance. Data were considered to be statistically significant at \(p < 0.05\).

**Results**

An uncertainty of 0.02 m was assumed for all data points used in kinematic calculations, which contributed to uncertainty in body length (BL) measurements of ±0.04 m. Maximum uncertainty of time measurements was ±1/30 seconds.

Average horizontal velocity ranged from 1.30 to 1.84 m/s. Means, SD and correlations with \(V_x\) for each variable are presented in table 1. Relative time spent in each phase, horizontal velocity during the DK, horizontal velocity during the UK, CM displacement during the DK, maximum vertical toe velocity during the UK phase, maximum chest flexion angle, maximum knee and ankle extension angles, and the ratio of flexion/extension for chest, knee and ankle angles correlated significantly with \(V_x\) (\(p < 0.05\)). The ratios of average DK vertical toe velocity/UK vertical toe velocity, and maximum DK vertical toe velocity/UK vertical toe velocity were significantly negatively correlated with \(V_x\) (\(p < 0.05\)).
Variables used to assess symmetry in the UDK

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
<th>r with $V_x$</th>
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</thead>
<tbody>
<tr>
<td>(a) Downkick Phase</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Downkick</td>
<td>15</td>
<td>45%</td>
<td>3%</td>
<td>0.486*</td>
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<tr>
<td>$V_{x\text{-DK}}$ (m/s)</td>
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<td>0.23</td>
<td>0.133</td>
</tr>
<tr>
<td>$V_{z\text{max-DK}}$ (m/s)</td>
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<td>-3.88</td>
<td>0.34</td>
<td>0.013</td>
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<tr>
<td>$\theta_{\text{CHEST-Flex}}$ (degrees)</td>
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<td>175</td>
<td>7</td>
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</tr>
<tr>
<td>$\theta_{\text{KNEE-Flex}}$ (degrees)</td>
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<td>121</td>
<td>7</td>
<td>0.405</td>
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<td>$\theta_{\text{ANKLE-Flex}}$ (degrees)</td>
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<td>142</td>
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<td>(b) Upkick Phase</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Upkick</td>
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<td>55%</td>
<td>3%</td>
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<tr>
<td>$V_{x\text{-UK}}$ (m/s)</td>
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<td>0.43</td>
<td>0.05</td>
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<tr>
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<td>15</td>
<td>191</td>
<td>8</td>
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<tr>
<td>(c) Downkick/Upkick Ratios</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Downkick / % Upkick</td>
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<td>0.1</td>
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<td>0.10</td>
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<td>0.21</td>
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<td>15</td>
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<td>0.16</td>
<td>-0.732*</td>
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<tr>
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<td>-0.3</td>
<td>0.4</td>
<td>0.517*</td>
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<td>-4.4</td>
<td>2.4</td>
<td>0.877*</td>
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<tr>
<td>$\theta_{\text{ANKLE-Flex}} / \theta_{\text{ANKLE-Ext}}$</td>
<td>15</td>
<td>-9.9</td>
<td>17.8</td>
<td>0.667*</td>
</tr>
</tbody>
</table>

Variables include: phase duration, horizontal CM velocities, kick displacement, vertical toe velocities, and joint angles are reported for (a) downkick phase, (b) upkick phase, and (c) ratios of downkick/upkick phases. N, maxima, minima, means, SD, correlation with $V_x$, and correlation with $V_x / BL$ are reported for each kinematic variable.

* correlation is significant at the p<0.05 level

**Discussion**

Our results supported the hypothesis that faster swimmers have a more symmetrical kick than slower swimmers, and that UK performance is significantly related to horizontal velocity; however, certain variables were more strongly related to UDK performance.

All swimmers spent more time in the UK than the DK phase; however, the faster swimmers tended to spend more similar amounts of time in each kick phase, whereas the slower swimmers tended to spend relatively less time in the DK and more time in the UK. This suggests that the relative amount of time spent in each phase may be a valuable indicator of UDK performance.

As expected, all measures of horizontal velocity were highly correlated with $V_x$, but average velocity during the UK showed the highest correlation with $V_x$. This provides evidence that faster swimmers are more proficient at the UK than slower swimmers. Surprisingly, the ratio of $V_{x\text{DK}} / V_{x\text{UK}}$ did not correlate significantly with $V_x$. Our initial hypothesis was that faster swimmers would maintain a more even velocity between DK and UK, but our results did not support that statement.

We observed that the $d_{x\text{-DK}}$ was significantly correlated with $V_x$. There was a small and non-significant correlation between $d_{x\text{-UK}}$ and $V_x$; similarly, there was a small and non-significant correlation between...
the ratio of $d_{x,DK} / d_{x,UK}$ and $V_x$. Because the displacement values do not consider the time spent during each phase, some swimmers with low kicking frequencies could travel long distances during a kick phase despite a low horizontal velocity. It appears that kick displacement is not a reliable measure of UDK performance or of kick symmetry since it does not take into account the time spent during each kick phase.

Maximum vertical toe velocity during the DK was not significantly correlated with $V_x$; however, $V_{zT_{max,UK}}$ was significantly correlated with $V_x$. In contrast, $V_{zT_{avg,DK}}$ and $V_{zT_{avg,UK}}$ were not significantly correlated with $V_x$. It appears that peak vertical toe velocities are more important than average vertical toe velocities for UDK propulsion. All swimmers achieved higher magnitudes of maximum vertical toe velocity during the DK than during the UK, but those who were more symmetric tended to have faster horizontal CM velocities. Generating similar propulsion during the DK and UK by having similar maximum vertical toe velocities appears to be most important for attaining high $V_x$.

Optimisation simulations of the UDK predict that swimmers who exhibited greater similarity between maximum joint extension and maximum joint flexion would have higher average horizontal velocities (Nakashima 2009). We observed evidence of this at the chest and it appears that upper thoracic flexibility is important for UDK performance. It is possible that the upper thoracic spine is used to a) dampen the body undulations of the lower body segments, and b) reduce resistive drag by maintaining a small angle of attack with the arms. We observed further evidence of this at the knee, indicating that less flexion and more hyperextension of the knee are related to UDK performance. Similar to the knee angle findings, our results indicate that less maximum dorsiflexion and greater maximum planar flexion of the ankle are related to UDK performance; this is consistent with the results from a simulation study of planar flexion angle in swimmers which suggested that, up to a certain point, an increase in plantar flexion angle would lead to an increase in UDK performance (Sugimoto, Nakashima, Ichikawa & Nomura 2008). These results indicate a relationship of mechanical symmetry and velocity at the chest, knee and ankle joints. Our results also indicate the importance of flexibility in the upper thoracic spine, the knee joint and ankle joint for UDK performance, in particular the ability to hyperextend the upper thoracic spine, knee and ankle joints.

**Conclusions**

This study tested the hypothesis that faster UDK swimmers would demonstrate a more symmetrical kick than slower UDK swimmers. These results suggest that hyperextended knees and ankles, and symmetrical knee and ankle angles between downkick and upkick phases are important for UDK horizontal velocity. The amount of time spent in each phase may also be an indicator of performance. It appears that most swimmers are able to perform the downkick successfully but have difficulty performing the upkick, likely due to anatomical restrictions at the knees and ankles. These results indicate the importance of kick symmetry for UDK performance, and indicate that performing the upkick phase well appears to be most important for UDK performance.

**Acknowledgments**


**References**


The effects of breathing on hip roll asymmetry in competitive front crawl swimming

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1University of Regina, Canada

Keywords: bilateral asymmetry, body roll, accelerometer, front crawl

Introduction

Front crawl swimming is a cyclic activity in which swimmers alternate arm and leg movements to create propulsive forces while the body rotates about its longitudinal axis. This motion is referred to as the body roll of the trunk. It has been suggested that breathing increases body rotation and potentially disrupts the symmetry of the stroke (Psycharakis & Sanders 2008). Inertial sensors are an emerging and accessible technology for quantifying movement in aquatic environments (Bachlin & Troster 2011). Previous studies have suggested that accelerometer derived data for stroke parameters can be as good as or better than data derived from video (Davey, Anderson & James 2008). This study quantified the effect of breathing on hip roll angle using a body-fixed tri-axial accelerometer.

Recent studies have shown that velocity and breathing are important factors affecting the degree of body roll during front crawl swimming. These studies have shown that as velocity increases, body roll of the trunk as a single segment decreases (Yanai 2003; Castro, Vilas-Boas & Guimaraes 2005) and that body roll, when the trunk is measured as a single segment (Payton, Bartlett, Baltzopolous & Coombs 1999) and when it is measured separately as hip and shoulder roll (Psycharakis & Sanders 2008), is greater when breathing than when not breathing. A further study by Psycharakis and McCabe (2011) suggested that whilst swimmers roll their shoulders and hips significantly more to the breathing side when breathing than when not breathing, the total body roll angle was not significantly different between breathing and non-breathing trials. The authors suggested that a compensatory strategy exists on non-breathing stroke cycles to maintain a similar total body roll angle to the breathing cycles.
One might assume that other cyclic locomotor activities such as walking, running and cycling would display symmetric movement patterns. However, research has shown that a degree of bilateral asymmetry is present in the propulsive forces of running and cycling (Sadeghi, Allard, Prince & Labelle 2000; Carpes et al. 2011). In front crawl, a unilateral breathing pattern is inherently asymmetric, as the swimmer will rotate more to the breathing side. In theory, a bilateral breathing pattern should prevent bilateral asymmetry; however, no previous studies have quantified the degree of body roll angle in bilateral and unilateral breathing conditions together.

Therefore, the purpose of this study was to determine the effect of breathing on body roll angle, specifically hip roll, in elite competitive front crawl swimmers. More specifically, the extent to which hip roll angle and hip roll asymmetry differed between unilateral and bilateral breathing conditions was investigated.

**Method**

Twenty university level competitive swimmers (thirteen males; age: 19.4±2.0 years, height: 180.8±7.8 cm, weight: 79.7±8.2 kg, and seven females; age: 19.1±1.0 years, height: 171.4±3.4 cm, weight: 67.3±7.2 kg) participated in the study. Institutional ethics approval was obtained from the Behavioural Research Ethics Board at the University of Regina and informed written consent was obtained from each participant prior to the commencement of the study.

A single body-fixed tri-axial accelerometer (GENEActiv, Cambridge, UK) was attached to an elastic waist belt and fastened around the hip of the swimmer on the back at the L5/S1 vertebrae. The accelerometer axes were aligned with the body such that the x-axis was in line with the spine, the y-axis perpendicular to the x-axis, and the z-axis vertical to the x and y-axes. The accelerometer was set to sample at 100Hz. Prior to entering the pool, participants were instructed to lie face down on the pool deck for 10 seconds. In this position zero degrees of roll was parallel to the pool deck. The data from this baseline calibration was averaged to calculate any offset due to sensor misalignment. Subsequently, the averaged value was subtracted or added to the calculated hip roll (HR) angle to correct for the offset caused by sensor placement.

Participants performed a series of three 100 m front crawl repetitions in a 25m indoor pool at a sub-maximal velocity equivalent to 70% of their season’s best 100m front crawl time. Each of the three 100m trials involved a different breathing pattern. The breathing patterns investigated were: 1) breathing to the preferred side every stroke cycle, 2) breathing to the non-preferred side every stroke cycle, and 3) breathing bilaterally every three strokes. The order of the trials was randomised for each participant and timed using a stopwatch to ensure that the velocity remained constant throughout and between the trials.

The participants began the trial from a standing start in the pool by pushing off the wall. At the end of each length, the participants performed a regular competition flip turn. Participants were allowed a full recovery of 3 minutes between trials to negate any potential effects of fatigue.

The raw X, Y and Z accelerations were processed using a low-pass digital filter set at a cut-off frequency of 4 Hz in Microsoft Excel (Microsoft Corporation, Washington, USA). Hip roll angles for each trial were calculated using the filtered acceleration data and the following tangential equation (Bachlin & Troster 2012);

\[ \text{Hip roll} = \arctan \left( \frac{z}{x} \right) \]

The peak HR angles on the left and right sides for each stroke were calculated. The HR angles were designated as preferred (P) side or non-preferred (NP) side and the mean peak HR angles for each side were determined. The mean total HR angle (mean peak angle for the P side + mean peak angle for the NP side) for each length and trial were also calculated.
The degree of bilateral asymmetry between the peak P and the peak NP side HR angles were calculated using an asymmetry index (ASI) adapted from one described by Robinson, Herzog & Nigg (1987):

\[ ASI_{HR} = \frac{(P-\text{NP})}{(P+\text{NP})} \times 100 \]

A series of repeated measures analysis of variance (RM ANOVA) were performed on the hip roll angle data to assess the influence of breathing. The first RM ANOVA used trial time as the within-subject variable to determine whether the trials were homogenous. The second RM ANOVA used length as the within-subject variable to determine whether HR angle changed within each 100 m trial. The next series of RM ANOVAs used the independent variables breathing (breath vs. non-breath), body side (preferred vs. non-preferred) and breathing condition (preferred side, non-preferred side and bilateral). The dependent variables used were mean total HR angle, mean peak HR angle for each side and mean ASI. In all cases, Bonferroni post-hoc analyses were performed to further identify any significant main or interaction effects. A value of \( p < 0.05 \) was considered to be statistically significant for all trials.

**Results**

The accelerometer signal revealed a clear and recognisable sinusoidal pattern as seen in Figure 1. No significant difference was found for the time taken to complete the trials (i.e., all trials were performed at the same speed). Additionally, no significant difference was found between lengths for HR angle, and therefore the four lengths were homogenous and could be used for further analysis.

![Figure 1](image)

Positive values indicate roll to the non-preferred side, negative values indicate roll to the preferred side.

**Figure 1**  A representative continuous hip roll angle for one length of a bilateral trial for one subject

The results of the RM ANOVA for peak HR angle demonstrated a significant main effect for condition and breathing. The results of the post-hoc t-tests to determine the effect of breathing are shown in Figure 2. Figure 2 demonstrates that in each condition, HR was significantly greater to the breathing side than the non-breathing side (\( p<0.05 \)). HR to the non-breathing side in the non-preferred condition was significantly greater than to the non-breathing side in the preferred condition. The peak HR value to the breathing side was not significantly different between conditions.
Error bars indicate ±1 standard deviation. * = significantly greater (p <0.05) than non-breathing side. # = significantly greater (p <0.05) than non-breathing side in preferred condition. For each condition, the preferred side (P) is shown first followed by the non-preferred side (NP) as the breathing (B) or non-breathing (NB) side.

**Figure 2**  Mean peak hip roll angle according to side and condition

Table 1 shows that total HR angle was significantly greater in the non-preferred condition than in the preferred condition. The preferred and non-preferred conditions demonstrated significantly greater ASI than the bilateral condition.

**Table 1**  Mean values for velocity, total HR angle and ASI by condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>Preferred</th>
<th>Non Preferred</th>
<th>Bilateral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>1.34±0.03</td>
<td>1.33±0.02</td>
<td>1.35±0.02</td>
</tr>
<tr>
<td>Total Hip Roll (°)</td>
<td>114.8±13.9</td>
<td>118.8±14.9 #</td>
<td>117.2±14.2</td>
</tr>
<tr>
<td>ASI (%)</td>
<td>20.2±7.5 *</td>
<td>-17.5±6.9 *</td>
<td>-4.1±2.8</td>
</tr>
</tbody>
</table>

# Significantly greater (p <.05) than preferred condition.  
* Significantly greater (p <.05) than bilateral condition.

**Discussion**

The results showed that peak HR angle was significantly greater to the breathing side compared to the non-breathing side in the preferred, non-preferred and bilateral conditions. Increased HR to the breathing side was expected, in that the importance of body roll as a mechanism to facilitate breathing has been reported previously (Psycharakis & Sanders 2008).

The magnitudes of the peak breathing and non-breathing HR angles are similar to those reported in a previous study using an accelerometer (Bachlin & Troster 2012). However, HR angles in this study are greater than those reported in previous studies using 3D video analysis (Psycharakis & Sanders 2008: Psycharakis & McCabe 2011). It should be noted that these values were recorded at much higher velocities (1.53-1.81 m/s) during maximal effort trials, and as such represent a likely source of the discrepancy. Castro et al. (2006) demonstrated that as velocity increases, body roll angle decreases. Similarly, Psycharakis & Sanders (2008) observed that a 0.23 m/s decrease in velocity throughout 200m caused an increase of 10.2° in HR angle. The mean velocity of the current study was 1.34 ± 0.06 m/s, so it is reasonable to expect that larger HR angles would be recorded, although it may not have
been the only source of difference between these angles and those previously reported in the literature.

Another possible explanation for the discrepancy in absolute HR angles is that the studies by Psycharakis & Sanders (2008) and Psycharakis & McCabe (2011) required subjects to control their breathing patterns through a 6.75m$^3$ recording zone. The change in breathing pattern for part of a length may have disrupted the natural stroke cycle rhythm and affected the angles that were recorded. Another limitation is that only one stroke cycle per length was analyzed. In the current study, every stroke cycle was analyzed, which resulted in the calculation of the continuous hip roll angle for approximately 8 stroke cycles per length, per trial. Therefore, data was collected for approximately 32 stroke cycles per subject per trial, compared to 4 (Psycharakis & Sanders 2008) and 1 (Psycharakis & McCabe 2011) per trial in the previous studies. Another possible reason for the differences in absolute HR angle could be experimental error associated with the use of the accelerometer. The method is based on the change in the gravitational acceleration vector from the anteroposterior to the mediolateral axis of the swimmer as the swimmer's body rotates through the water. While non-gravitational acceleration along both of these axes is minimal during swimming, it is possible that for some subjects anteroposterior and/or mediolateral motion of the pelvis was also recorded by the accelerometer and resulted in a slightly larger hip roll angle determination. It should be noted that this potential source of error was a systematic error and would not have affected the results, as the statistical comparison of conditions was based on within-subject comparisons.

Total HR angle was significantly greater in the unilateral, non-preferred condition than the preferred condition. This is explained by a significantly greater non-breathing peak HR angle to the P side (54.3°) compared to the NP side (51.7°) in the two unilateral conditions. This demonstrates that swimmers rolled their hips more to the preferred side when not breathing than to the non-preferred side.

The HR to the breathing side was significantly greater than to the non-breathing side, resulting in a significant bilateral roll asymmetry. This was shown by calculating the ASI, such that the preferred condition demonstrated the highest ASI (20.2%), followed by the non-preferred condition (-17.5%). It is interesting to note that the absolute level of asymmetry for unilateral breathing was similar despite the fact that the total HR angle of the non-preferred condition was significantly greater than the preferred condition.

In the bilateral breathing condition, it was expected that the HR angle would be less asymmetric than in the unilateral breathing conditions. This was the case, as the peak HR angles for the preferred and non-preferred sides were similar for breathing (62.8° vs. 63.7°) and not breathing (53.8° vs. 54.2°). When looking at the ASI for the bilateral condition, the mean HR angles to the preferred side (i.e., breaths and non-breaths) were combined and compared to the angles for the non-preferred side (breaths and non-breaths). This resulted in an ASI of -4.1% to the non-preferred side, which was significantly lower than the other two conditions. The bilateral breathing pattern appears to neutralise the effect of breathing on roll asymmetry, as the rolling pattern of the swimmer is balanced as the breathing alternates from side to side (i.e., breathing every 3 strokes or 1.5 stroke cycles).

Therefore, by breathing to both sides, there is less roll asymmetry than when breathing to one side only.

**Conclusions**

The findings demonstrate that breathing patterns affect hip roll asymmetry when performing front crawl at a submaximal speed, such that unilateral breathing exhibits greater asymmetry than bilateral breathing. This supports the idea that bilateral breathing is beneficial and can reduce hip roll asymmetry. The results also demonstrate the practical application of using an accelerometer to quantify hip roll angle in competitive front crawl swimming.
References


Freestyle arm entry effects on shoulder stress, force generation, and arm synchronisation

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¹Everett Pacific Industrial Rehabilitation, USA, ²Swimming Technology Research, USA

Keywords: biomechanics, coordination, injury, performance, swimming

A previous study showed that immediately after the arm entry, female butterfly swimmers were not efficient in 30% of the stroke cycle because their arms were in a biomechanically disadvantageous position (Becker & Havriluk 2010). The swimmers completed their arm entry with their hands closer to the surface than their shoulders in a position that stressed their shoulders. They generated minimal force until the hands submerged below the level of the shoulders. In a subsequent study on male and female freestyle swimmers (Havriluk & Becker 2011), over half of the swimmers (mostly females) completed the arm entry with their hand closer to the surface than their shoulder in a stressful position similar to butterfly. Given the prevalence of shoulder injuries from butterfly and freestyle (e.g. Hupenthal 2006; Rodeo 2011), further examination of the arm entry is appropriate.

The present study was designed to determine the prevalence of an ineffective arm entry in freestyle and the impact on shoulder stress and force generation. Because of the wasted time from an ineffective arm entry position, the effect on arm synchronisation was also calculated. Due to the previously found gender difference in arm entry, the variables were stratified by gender.
**Method**

The study included 40 university swimmers (20 males and 20 females). The descriptive statistics for the males were: height in cm (M = 186, SD = 5.6) and mass in kg (M = 85.6, SD = 8.3). The descriptive statistics for the females were: height in cm (M = 165, SD = 5.6) and mass in kg (M = 61.9, SD = 7.3). Swimmers were tested swimming one trial of freestyle over a 20 m course using a protocol identical to the butterfly study (Becker & Havriluk 2010). Synchronised underwater video and force data were captured over the last 10 m of the swim (Figure 1).

![Figure 1](image)

**Figure 1**  Aquanex with force gap and overlap. The vertical gray lines on the force curves are synchronised with the video image. Force curves for the opposite hand are in outline

At the completion of the arm entry, the position of the hand with respect to the depth of the shoulder was determined. Stroke cycles were analyzed to determine the time that hand force generation began (HFB) and ended (HFE), as well as the time that the hand submerged below shoulder level (HSS). The time of exposure to maximum shoulder stress (exposure phase) was defined as the time between the beginning of force generation and when the hand submerged below the level of the shoulder (HSS–HFB). The pull phase began when the hand submerged below the level of the shoulder (HSS) and ended when the hand passed vertically beneath the shoulder (HVS). The push phase began when the hand passed vertically beneath the shoulder (HVS) and ended at the finish of force generation (HFE). The average force during the exposure phase (HSS – HFB), the pull phase (HVS – HSS), and the push phase (HFE – HVS) was calculated.

Arm synchronisation was analyzed using two events at the beginning of the underwater arm motion (HFB and HSS) and one event at the end of the underwater arm motion (HFE). The gap or overlap between hands in force generation was determined as the difference between arms for both HFE – HFB and HFE – HSS.
**Results**

As shown in Figure 2, most females (70%), but only 10% of males completed the arm entry with the hand closer to the surface than the shoulder (above shoulder). Over 80% of the males completed the arm entry with the hand at the same level as the shoulder (shoulder level). There were only two swimmers (both males) who completed the arm entry with the hand deeper than the shoulder (below shoulder). Since only males entered below the shoulder, the below shoulder data were collapsed with the shoulder level data. Right and left arm data were then identical with above shoulder entry for 14 females and 2 males and shoulder level and below entry for 6 females and 18 males. The interaction of gender by entry level was significant (p < .05) with $\chi^2 = 15$.

![Figure 2](image.png)

**Relative position of the hand with respect to the shoulder at the completion of the freestyle arm entry**

The gender difference in the position of the arm at the completion of the entry resulted in a difference in the time required to submerge the hand below the level of the shoulder (time of exposure to maximum shoulder stress). As shown in Figure 3, the female time of exposure was .17 sec more than the duration for the males (p<.05) or about 2.5 times as long for both arms.

![Figure 3](image.png)

**Time of exposure to maximum shoulder stress (the time between the beginning of force generation and when the hand submerged below the level of the shoulder or HSS - HFB)**
The males generated significantly more force than the females \((p < .05)\) for both arms on all three phases (Figure 4). When the pull and push phases were analyzed, there was a significant gender by phase interaction \((F = 16.93, p < .05)\). The males significantly increased force from the pull phase to the push phase, but the females did not.

![Figure 4](image)  
**Average hand force during three phases of the underwater arm motion**

Males and females had a similar overlap in hand force between arms when determined by the beginning and end of hand force generation \((HFE-HFB)\), as shown in Figure 5. There was about a .2 sec overlap with the beginning of force with one hand and the finish of force generation with the other hand. However, when using the event of the hand submerged below the level of the shoulder and in position to generate propulsive force at the beginning of the pull \((HFE – HSS)\), the males had an overlap of about .1 sec while the females had a slight gap between hands in force generation.

![Figure 5](image)  
**Force gap or overlap for two calculations of arm synchronisation – beginning and end of hand force generation \((HFE – HFB)\) and beginning and end of propulsive force generation \((HFE – HSS)\)**

**Discussion**

The data show a dramatic difference between males and females in arm position on entry. The females usually completed the arm entry with the hand closer to the surface than the shoulder (above shoulder), while the males usually completed the arm entry at shoulder level. The arm entry...
difference resulted in a much longer time of exposure to maximum shoulder stress for the females (.17 sec).

Only 2 of 40 participants completed the arm entry with the hand deeper than the shoulder (both males). Since only trivial (and non-propulsive) force was generated before the hand submerged below shoulder level, almost all participants in this study could improve their arm entry with a downward angle. As previously recommended, completion of the arm entry with the hand below the shoulder positions the arm to immediately generate propulsive force at the beginning of the pull as well as reduce shoulder stress (Havriluk 2012). For example, the swimmer in Figure 1 completed the arm entry with the hand below shoulder level and increased his force to over 40 N in less than .1 sec.

When arm synchronisation was analyzed using the beginning and end of hand force generation (HFE – HFB), males and females both had an overlap between arms of about .2 sec. However, females required .17 sec more than males to submerge the hand below shoulder level. When the arm synchronisation was analyzed using the event of the hand submerged shoulder level and the end of hand force generation (HFE – HSS), there was an overlap in force for the males (as exemplified in Figure 1), but a gap for the females. In addition to the females risking a longer time of exposure to maximum shoulder stress, they also suffer a performance limitation with a gap between arms in propulsive force.

Seifert (2010) summarised that expert swimmers have an overlap in propulsion (also called superposition). Richards (2006) commented that an effective freestyle had ‘no gaps in propulsion’. An effective arm entry angle (for females in particular), would not only reduce shoulder stress and position the arm to immediately generate propulsive force, but also improve arm synchronisation so that there were overlaps in propulsion between arms.

The gender difference in time of exposure to maximum shoulder stress may be explained by a combination of flexibility and water resistance. As females generally have greater shoulder flexibility than males (Borsa, Sauers & Herling 2000), the water resistance during arm entry might make it more natural for a female to use a greater range of motion rather than exert effort to overcome resistance. For example, the swimmer in Figure 6 begins the arm entry with a downward angle (left image), but changes the angle as the arm straightens (right image). The position of the hand at the completion of the arm entry is above the shoulder resulting in only a trivial amount of force generated until the hand submerges below the shoulder.

An intentional effort to complete the arm entry with the arm parallel to the surface is a technique factor that contributes to an ineffective arm position, shoulder stress, minimal force generation, and

Figure 6  The swimmer begins the arm entry with a downward angle (left image), but changes the angle as the arm straightens (right image)
gaps in propulsion. When the arm is intentionally maintained in position parallel to the surface (as in catch-up stroke), torso rotation increases the time of exposure and exacerbates shoulder stress.

The hand force data for the pull and push phases suggests another opportunity for females to improve performance. Males increase force from pull to push, but females fail to increase force. The females’ effort to submerge the entry arm below the shoulder may distract them from making an effort to increase force on the push phase of the other arm. The results of this study suggest that males can have some benefit from a more effective freestyle arm entry and that females can have substantial improvements.

The event of completing the arm entry with the hand below shoulder level is critical to minimising shoulder stress, maximising force generation, and optimising arm synchronisation. Fortunately, the arm entry can be evaluated from the pool deck. Coaches can assess swimmers’ arm position as it straightens. Feedback about the relative orientation of the hand and the shoulder at the completion of the arm entry can help swimmers make a technique adjustment of major importance to both minimise the risk of shoulder injury and maximise performance.

**Conclusions**

The gender difference in the arm entry resulted in a much longer time of exposure to maximum shoulder stress for the females. Because the females required so much time to submerge the hand below shoulder level, the arm synchronisation showed a gap between arms in generation of propulsive force. In contrast, the males had an overlap between arms in propulsive force generation. Both males and females can improve their arm entry to minimise the time of exposure and maximise the force generation overlap. Males also significantly increased their hand force from the pull phase to the push phase, while females did not. If females improve their arm entry, they may also be able to focus more effort on the push phase.

**References**


Evaluation of competitive jammers in expert male crawl swimmers

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Keywords: competitive swimsuits evaluation, performance and biomechanical tests, compression gradient, computational fluid dynamics simulation, drag force

Introduction

The evolution of rules about competitive swimsuits requires updating current scientific data: for example, the biomechanical and physiological consequences of garments with compressive properties show mixed results (Benjanuvatra et al. 2002; Chollet et al. 2010; Marinho et al. 2012; Tomikawa & Nomura 2009).

Indeed, the studies concerning swimsuits are often contradictory and some clarification is needed. Some authors showed no significant reduction in drag and no increase in buoyancy with a Fastskin swimsuit (Roberts et al. 2003; Toussaint et al. 2002) while Chatard and Wilson (2008), comparing a traditional suit, a full-body suit and a waist-to-ankle suit, found significant reduction in passive drag in the latter two. They also showed that Fastskin suits increased distance per stroke, whereas there was no significant difference in stroke rate. Mollendorf et al. (2004) tested several swimsuits and noted some small but significant differences in total drag between these suits. At low speed, pressure drag seemed to be the most important component. At high speed, skin friction drag was increased and pressure drag and wave drag were reduced for two different suits. According to Benjanuvatra et al. (2002), Fastskin suits did not increase buoyancy. However, they seemed to significantly decrease active and passive drag forces when towing.

In swimming, five criteria can help to define the use of appropriate swimsuits, namely 1) the discipline (e.g. triathlon, long distance, sprint), 2) the gender, 3) the morphological properties of the swimmer, 4) the physical properties of the swimmer (e.g. glide quality, buoyancy), and 5) the evolution of rules regarding these swimsuits (today limited, for men, to jammers).

The logic behind using special swimsuits is to improve buoyancy what was argued in the context of triathlon (Hue, Benevante & Chollet 2003). For the same swimming speed, the improvement allowed by these suits effectively reduces the propulsive phases and increases gliding, relationship that is measured by the coordination index (IdC; Chollet, Chalies & Chatard 2000). For the distance of 800m, this improves swimming coordination of those triathletes wearing the swimsuit (versus triathletes not wearing the swimsuit) by spending more time in non-propulsive glide during the catch phase.

Besides, it was shown in a study comprising 9 females and 9 males at 100-m distance race pace (Chollet et al. 2010), that the use of Fastskin swimsuits showed no significant difference in buoyancy, glide or passive hydrostatic torque, but significantly influenced the IdC and resulted in more efficient propulsive actions for the same given speed. Indeed, the Fastskin suit significantly affected the values describing the propulsive phases: the glide phases increased and consequently propulsive phases were reduced. In accordance with previous studies, our analysis confirmed that, at increased speeds, the IdC increases (Chollet et al. 2010). The reduction in IdC with the Fastskin suits was significant for the global analysis, but a closer examination revealed that this was only significant for the 100-m velocity. It thus appears that, besides the claims of improved buoyancy, the improvements of those new generation suits are greater for high rather than low velocities. One possible interpretation is that the compressive effect of these new suits, by reducing body volume and thus lowering buoyancy, is offset by an improvement of the drag coefficient due to this compression. The effects measured in
the older generation suits, which were more useful for long distances and triathlons (Chatard et al. 1995; Hue, Benavente and Chollet 2003; Toussaint et al. 2002), no longer hold for this newest generation. The compression of body volume is thus more useful for high speeds than for slower speeds.

After more than 100 world records were broken in 2008, FINA has decided to significantly modify the rules, namely that the swimmers are not allowed anymore to wear full-body, full-legs or polyurethane suits. Moreover, all accredited jammers do not have the same characteristics and their impacts on performance could be different.

Hence, the aim of this study was to compare four different competitive jammers relative to the personal usual training swimsuit in well-trained swimmers, based on a large set of different tests.

**Method**

Eighteen male expert crawl swimmers participated in this study.

**Experiment 1**

Ten participants (see anthropometric and performance data, Table 1) performed five randomised exercise sessions (jammer JA, JB, JC, JD and a control SS).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Characteristics of the ten male swimmers involved in the first experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>Height (cm)</td>
</tr>
<tr>
<td>Mean</td>
<td>19.5</td>
</tr>
<tr>
<td>S.D.</td>
<td>2.7</td>
</tr>
<tr>
<td>Min</td>
<td>17</td>
</tr>
<tr>
<td>Max</td>
<td>25</td>
</tr>
</tbody>
</table>

*Performance level is the ratio between the 200 m freestyle world record and the swimmer’s best performance. S.D. means standard deviation.

Each session involved an all-out 200-m crawl and a 50-m leg trials after a standardised warm-up. For the 200-m crawl, heart rate was continuously recorded during the trial (Polar team system, Kimpele, Finland) and blood lactate was analysed before and after the trial (Lactate Pro, Arkray, Tokyo, Japan). Ratings of perceived exertion (Borg scale) and rate of perceived effect of swimsuit on performance realisation (feedback questionnaires) were also obtained after the 200-m crawl. Anthropometric measures, buoyancy and glide completed the set of tests.

**Experiment 2**

Eight participants (see anthropometric and performance data, Table 2) were involved in the second experiment.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Characteristics of the eight male swimmers involved in the second experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Age (yrs)</td>
</tr>
<tr>
<td>20.9</td>
<td>181.5</td>
</tr>
<tr>
<td>S.D.</td>
<td>5.7</td>
</tr>
<tr>
<td>Min</td>
<td>15</td>
</tr>
<tr>
<td>Max</td>
<td>28</td>
</tr>
</tbody>
</table>

**Performance level corresponds, in FINA points, to the swimmer’s best performance. S.D. means standard deviation.

A three-dimensional scan has been done on each swimmer wearing each jammer (JA, JB, JC, JD and SS; Figure 1). The 3D surface geometry model was acquired through standard commercial laser scanner CX-PRO 3D scanner (4DDynamics, Antwerp, Belgium). The swimmers were in rest along the body scans. Each scan took an average of 20 minutes. Care was taken to limit differences in alignment.
of the individual scans for the five situations, by fixing the position of feet, maintaining similar vertical and horizontal alignment in respective scans and also the stationary pose with control of breathing during the actual moment of acquiring the scan (Lashawnda & Cynthia 2002). The swimmers presented their arms extended above the head (shoulders flexed), with one hand above the other (streamlined position).

Figure 1  Body position during 3D scans

3D geometric models were used for analysis through computational fluid dynamics (CFD) simulation. Simulations were carried out in Ansys Fluent™ 6.3 commercial software (Ansys, Canonsburg, Pennsylvania, U.S.A.), using finite volume method of discretisation. The quadrilateral computational domain of 20 m length, 1.5 m breadth and 1.5 m height with inlet at 5 m upstream of the swimmer model was prepared in Gambit™ preprocessor (Ansys, Canonsburg, Pennsylvania, U.S.A.). The computational domain consisted of about 11 thousand tetrahedral grid cells. Passive drag was determined with the swimmer model at a depth of 0.75 m. Drag force and drag coefficient were computed for a steady flow velocity of 2.0 m.s$^{-1}$. Pressure drag component and skin friction drag component were also computed.

Results

Experiment 1

Table 3 shows the results obtained for the main variables. The order effect was controlled by randomising the trials so that during each session two swimmers performed the test in one jammer condition.

The performance score appeared significantly higher in the jammer condition compared to the control condition.

Table 3  Comparisons of swimsuit and jammers for the 200-m crawl and biomechanical tests

<table>
<thead>
<tr>
<th></th>
<th>Swimsuit</th>
<th></th>
<th>Jammers</th>
<th></th>
<th>Contrast tests*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>S.D.</td>
<td>n</td>
<td>Mean</td>
<td>S.D.</td>
</tr>
<tr>
<td>200-m crawl (s)</td>
<td>127.34</td>
<td>4.22</td>
<td>7</td>
<td>122.42</td>
<td>4.29</td>
</tr>
<tr>
<td>Race laps’ variability (s)</td>
<td>0.55</td>
<td>0.30</td>
<td>7</td>
<td>0.45</td>
<td>0.16</td>
</tr>
<tr>
<td>Borg scale</td>
<td>5.5</td>
<td>2.3</td>
<td>6</td>
<td>4.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Glide (m)</td>
<td>12.03</td>
<td>2.80</td>
<td>7</td>
<td>12.95</td>
<td>2.49</td>
</tr>
<tr>
<td>Vertical position recovery (s)</td>
<td>6.54</td>
<td>0.68</td>
<td>7</td>
<td>6.35</td>
<td>0.59</td>
</tr>
<tr>
<td>Buoyancy (kg)</td>
<td>2.954</td>
<td>0.692</td>
<td>7</td>
<td>2.753</td>
<td>0.718</td>
</tr>
</tbody>
</table>

*Five imputations were computed to estimate missing values.
S.D. means standard deviation.
n.s. means non significant.

Figure 2 shows on a normalised scale (i.e. between 0 and 1) the comparative values of all measured variables.
Experiment 2

Concerning the passive drag, Table 4 shows that jammers A and B exhibited a total drag 5% lower than the swimsuit, whereas jammers C and D showed only 2.5% lower total drag compared to the swimsuit.

To complete these results, it appeared that:

- The main differences were observed in pressure drag component, highlighting the paramount role of jammer on thigh compression;
- Six of 8 swimmers presented lower passive drag values when wearing the jammer A;
- Two of 8 swimmers presented better hydrodynamic results with the jammer B compared with the others and their usual training suit;
- The jammer B always presented better results than jammer C;
- Only 2 swimmers presented better results when wearing jammer D compared with jammer B.
Table 4: Mean (S.D.) values of drag coefficient and drag force (with pressure and friction drag components) of the eight swimmers wearing the swimsuit and the four jammers

<table>
<thead>
<tr>
<th></th>
<th>SS</th>
<th>JA</th>
<th>JB</th>
<th>JC</th>
<th>JD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total drag (N)</td>
<td>43.202 (9.382)</td>
<td>40.765 (8.331)</td>
<td>41.179 (8.791)</td>
<td>41.998 (9.188)</td>
<td>41.910 (8.810)</td>
</tr>
<tr>
<td>Pressure component</td>
<td>30.190 (5.525)</td>
<td>27.799 (7.333)</td>
<td>28.144 (7.717)</td>
<td>28.966 (8.063)</td>
<td>28.845 (7.720)</td>
</tr>
<tr>
<td>of the drag force (N)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friction component</td>
<td>13.012 (1.047)</td>
<td>12.965 (1.107)</td>
<td>13.035 (1.171)</td>
<td>13.032 (1.189)</td>
<td>13.066 (1.187)</td>
</tr>
<tr>
<td>of the drag force</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>0.224 (0.026)</td>
<td>0.213 (0.023)</td>
<td>0.213 (0.023)</td>
<td>0.219 (0.024)</td>
<td>0.219 (0.024)</td>
</tr>
<tr>
<td>Pressure component</td>
<td>0.156 (0.027)</td>
<td>0.145 (0.024)</td>
<td>0.145 (0.024)</td>
<td>0.150 (0.025)</td>
<td>0.150 (0.024)</td>
</tr>
<tr>
<td>of the drag coefficient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friction component</td>
<td>0.068 (0.005)</td>
<td>0.068 (0.004)</td>
<td>0.068 (0.004)</td>
<td>0.069 (0.004)</td>
<td>0.069 (0.004)</td>
</tr>
<tr>
<td>of the drag component</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decrease of passive drag in comparison with SS (%)</td>
<td>-5.159</td>
<td>-4.99</td>
<td>-2.531</td>
<td>-2.539</td>
<td></td>
</tr>
</tbody>
</table>

**Discussion**

Through this experiment, the jammer appeared to improve the chronometric timing, as the time for 200-m front-crawl in the jammer conditions was significantly lower than in a swimsuit. Conversely, the use of jammers did not affect the perceived exertion with the Borg scale or the management of the race compared to the control condition. This significant difference appears also between the swimsuit and the jammer A (p = 0.019, post hoc tests between the 5 conditions JA, JB, JC, JD and SS).

The absence of significant differences for the other variables associated to performance than the time in 200-m crawl could be interpreted from different manner. Indeed, a difference in the Borg scale could have indicated a differential effect of wearing a jammer vs. wearing a swimsuit, but also a difference of involvement in the task (e.g. a swimmer wearing a swimsuit less motivated than when he swam with the jammer), therefore impacting the differences in terms of performance. It appears that the increase in performance with the jammer condition could be actually due to the jammer and not only to a differential implication in the task.

Concerning the differences between jammers and swimsuit in the biomechanical tests, these differences appeared all non-significant. However, jammers tended to improve the glide, to decrease the buoyancy capacity and to lower the point of application of the Archimedes hydrostatic lift (through mass compression and decrease of the thigh volume).

A precise analysis between each jammer and the swimsuit showed a significant difference between the swimsuit and the jammer B for the circumference of the thigh above the knee (the end part of the jammer, variable called bottom jammer’s tour in Figure 2) and the ratio between the circumferences at the mid-thigh and above the knee (mid-thigh/bottom ratio in Figure 2), suggesting that the compression of the thigh tends to move the volumes down where the compression would be less. The significance was close between jammer B and jammer D for the mid-thigh/bottom ratio, suggesting that the compression gradient is different between the different models of jammer.

These kinds of differences could have an incidence on the swimming speed mainly at sub-maximal speed (i.e. for long-distance or triathlon events) or for highly dense individuals (e.g. triathletes or sprint swimmers), and less at maximal speed (i.e. short-distance events).
Conclusion

The tests showed few discriminating results between all conditions. Overall, the time to perform 200-m crawl in the jammer conditions was less than in the control swimsuit condition. Finally, the time was significantly less in condition JA than SS.

This study, limited to male swimmers, should be very instructive for female swimmers in so far as the compression volume is much more important for female.

References


Dubious use or misuse of scientific information in commerce and policy making e.g. the swimsuit case

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Keywords: drag, turbulence, swimsuits, high-tech surface coating, skin fasciae, fasciae mechanics

Abstract

Regardless the active resistance data acquisition variance between the Marine Test Station (Brussels-Wageningen) data, the Swimming Flume (Stockholm) findings, the Measuring Active Drag (MAD-Amsterdam), the device for measuring active drag (DAD-Beijing) or the Velocity Perturbation Method (VPM), these approaches do not interfere with the direct obtained values of passive drag e.g. Ds versus Dp and with our laminar and turbulent flow knowledge. The aim of this project is to re-evaluate resistance data of the end of previous century in combination with interpretations of the High-technology swimwear studies (2000-2010). Commercial justifications of Drag-versus
morphology data versus the non-dimensional form relation, have been ignored. The continuous body shape deformations at Ds level are subject of a violation of basic hydrodynamic reasoning. The impressive quantity of records with the High-Tech swimwear was probably a sufficient argument – even misleading—to accept all quality issues claimed by the manufacturer.

But why ban High-Tech swimwear which facilitates movement only e.g. the fascia theory. In cycling the aerodynamic outfit and bike design improve performance at a level of seconds and minutes over distance. Nor the High-Tech swimwear, nor the aerodynamics hardware in cycling do overrule the individuals training and performance effort. Dubious argument acceptance or discriminating morality?

**Introduction**

At the end of the first decennium of this century an unprecedented amount of swimming world records have been broken, e.g. over 130. These records and the series of medal winners at Olympic Games are indisputable associated with the High-Technology swimwear and the developed fabrics.

High-Technology swimwear fabrics are scientifically advanced materials used for competitive water sports such as swimming and triathlon. Materials of this type are normally spandex and nylon composite fabrics with features to reduce drag against the water (Wikipedia 2013).

The High-Tech fabric lines and the substantial advantages for swimmers were heavily debated. Manufacturers claimed that swimming velocity would increase up to 7% as a result of a reduction of drag, frictional drag in particular. The Fastskin, e.g worn by most Olympic swimmers, was promoted for reducing drag up to 4%. It fabric was meant to resemble shark’s skin, e.g. tiny triangular projections that point backward so that the water spirals off the athlete’s body. Most of the manufacturers counter with their own studies to promote the advantages of their own individual lines, but they all focus on hydrodynamics e.g. drag reduction, frictional resistance in particular, not only for ‘glide’ situations, but for swimming also.

Most mentioned features include enhanced glide through the water, due to marine animal skin mimic, water-repellent, muscle compressing, the swimmers’ posture and blood circulation improving. Although heavily debated, the facts itself, e.g. the records, are the evidence of the advantages provided by the High-Tech swimsuits. Increases in whole body velocities (v) ranging between 3 and 12% (Oeffner and Lauder 2012) and segmental increases of V (Rogowski et al. 2006) e.g. as direct data acquisition of swimsuit coating and texture explains by fact the unprecedented world performances. The step from velocity enhancement to resistance reasoning is logic due to its known relations. It explains why studies of both manufacturers and researchers suggest that the benefits of the High-Tech swimsuits are due to passive and active swimming drag reduction, including a calculated decrease of frictional (Df) and wave making drag (Dw) (Polidori et al. 2006; Rogowski et al. 2006; Mollendorf et al. 2004; Toussaint et al. 2002).

The reality may be the wrong focus of the manufacturer and the missing reliability studies of their methodology leading to accurate values, separate for both Dp and Ds.

The quantity of records using the High-Tech swimwear is by its evidence a sufficient argument to accept all quality issues claimed by the manufacturer but this reasoning has been tackled (Toussaint et al. 2002). It is not unusual that the manufacturers reliability differs from the reliability of the user e.g. system versus observer reliability. It needs reminding that there is a distinct discrepancy between Ds and Dp, but not necessarily in its quantitative expression. Regardless the known methodological differences of drag data acquisition between the Marine Test Station data (Brussels-Wageningen), the Swimming Flume findings (Stockholm), the Measuring Active Drag-MAD system (Amsterdam), the Device for measuring Active Drag (DAD-Beijing) or the Velocity Perturbation Method (VPM) system values (Clarys 1985, Holmér and Haglund 1978, Toussaint et al. 2004, Xin-Feng et al. 2007, Kolmogorov and Duplisheva 1992), this principal cannot be denied. The discrepancy between Dp as the gliding part and Ds as the movement part of swimming is surpassing the boundaries of
hydrodynamics and the law of similitude, including Laminar and Turbulent flow phenomenae. Gliding is an attempt of body streamlining and as such it is different from the swimming motion that deforms the streamlining.

Even though $D_s$ obtained with the MAD and DAD systems are almost equal to $D_p$ values (van der Voordt et al. 1987; Wang et al. 2007) the basic biological motion discrepancy remains due to the substantial and transient shape changes during the swimming stroke. In other words, even with $D_s$ values equal to $D_p$ values a transfer of morphological relations with repeatable measurements e.g. Anthropometry/Body Composition to a continuous deforming body is a violation of biological evidence.

The purpose of this study is to combine published and non-published drag data verifying (i) morphological body composition components within a $D_p$ and $D_s$ breakdown (ii) associated and recent muscle mechanics information (iii) the clarification of the various explanations given of the broken records with High-Tech swimsuits.

Since this has led to a ban of these suits in official competitions a comparable aerodynamic case will be presented, within the domain of federation politics and morality.

**Methods**

The passive drag ($D_p$) forces in a prone position two arms forward at the water surface and 60 cm under the water, in an 45° inclined position over the longitudinal axis of the body, one arm forward and both active drag ($D_s$) were measured in a Marine Model and Ship design test station. The test were carried out in a 200 m long, 4 m deep and 4 m large basin, the subjects being connected with a telescope force transducer device to a Velocity controlled and electrically driven towing carriage (4x4x2.5 m) on which all data acquisition instruments were mounted (Clarys 1979,1985). Published and non-published data material has been collected of 44 Physical Education (PE) students, 9 elite swimmers and 6 athletes with extreme different body constitution (3 ectomorphs and 3 meso-endomorphs) (table 1). Passive drag data were collected, in temperatures of 18° and 24° C. and related to body morphology with anthropometric transfer of direct values to non-dimensional hydrodynamic indexes. Both passive and active data are based on direct registration of the electrical force patterns without extrapolation nor calculation (Fig. 1). This to avoid discussion of methodological nature e.g. (MAD versus Flume; Versus Marine test station a.o.).

![Figure 1](image)

*Figure 1*  Averaged force signals measured in mm to a zero baseline (arrows)

<table>
<thead>
<tr>
<th>Sample (N)</th>
<th>$H$(cm)</th>
<th>$W$(kg)</th>
<th>$\Delta$(l)</th>
<th>$S$(m$^2$)</th>
<th>$X$(cm$^2$)</th>
<th>$H/B$</th>
<th>$B/D$</th>
<th>$H/D$</th>
<th>$H^2/S$</th>
<th>$H^2/X$</th>
<th>$H/\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elite (9)</td>
<td>183.9</td>
<td>72.9</td>
<td>67.8</td>
<td>1.677</td>
<td>766.7</td>
<td>4.4</td>
<td>2.1</td>
<td>8.9</td>
<td>2.0</td>
<td>44.9</td>
<td>4.6</td>
</tr>
<tr>
<td>Students (44)</td>
<td>180.9</td>
<td>73.8</td>
<td>68.4</td>
<td>1.665</td>
<td>767.4</td>
<td>4.4</td>
<td>2.0</td>
<td>8.9</td>
<td>1.9</td>
<td>43.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Ecto (3)</td>
<td>187.9</td>
<td>71.5</td>
<td>65.9</td>
<td>1.657</td>
<td>714.9</td>
<td>4.4</td>
<td>2.3</td>
<td>10.0</td>
<td>2.1</td>
<td>50.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Endo-Meso (3)</td>
<td>180.1</td>
<td>113.0</td>
<td>107.2</td>
<td>2.283</td>
<td>1020.1</td>
<td>4.2</td>
<td>1.7</td>
<td>7.2</td>
<td>1.4</td>
<td>32.0</td>
<td>3.8</td>
</tr>
</tbody>
</table>

$\Delta$: Volume in max. expiration; $H$: Height; $W$: Weight; $S$: Surface; $X$: Cross section; $B$: Breadth of thorax; $D$: Depth of thorax.
Results and discussion

From Table 1 two preliminary observations deserve attention. The basic morphological, dimensional measures and the non-dimensional hydrodynamic indexes do not discriminate PE students from Elite swimmers and their overall Body Composition corresponds best with the selected ectomorph types (H excluded). These selected ‘extreme’ types however are chosen because of their lean versus corpulent difference. Observation of the Dp graphics (Fig. 2 and 3) allow for more speculations. Morphological discriminating body formats and the greatest body cross-section, in particular, influence Dp less than the water temperature and the body position. Fig. 2 combines Dp of students, ectomorphs, endomesomorphs and Elite Swimmers both prone and 45° longitudinal inclined at the water surface and 60 cm under the water surface. Elite Swimmers and students are not morphologically different but the better positioning e.g. alignment makes the drag difference. The extreme somatotypes do confirm their morphological difference. The 45° inclined and prone under water drag difference likewise suggests the importance of the positioning.

![Figure 2](image-url)  
**Figure 2** Dp positioning and morphology

![Figure 3](image-url)  
**Figure 3** Non-dimensional temperature differences

Observe in Fig. 2 the D difference between Elite and PE students, realising both groups have an identical morphology. The water temperature at and under the water surface and the body position e.g. alignment are far more discriminating for Dp (Jiskoot en Clarys 1975, Clarys 1979) than morphology. The observation of the non-dimensional representation of Dp at temperatures of 18° and 24°C (Fig. 3) is significant (P<0.01) for that matter in both the horizontal position 60 cm under and at the water surface. According to the theories of laminar and turbulent flow as a function of the drag coefficients (CD) and Reynolds number (Re) there is no doubt that a turbulent flow occurs around the human body. For all values beyond the transition line, the turbulence increases with CD values as a function of Re. For the human body the turbulent flow is very high (Fig. 4). According to hydrodynamic principles the turbulent flow around the body is associated with an increase of pressure resistance (Lamb 1997 and many others). This confirms the hypothesis that the boundary layer around a passive human body moving (e.g. towed) through the water is totally turbulent and originates from different and variable boundary layer separation at the head, neck, shoulders, lumbar region, hips, thighs, knees and feet (Clarys 1979; Mollendorf et al. 2004).
In the towing experiments, 60 cm under the water surface, the Reynolds (Re) numbers and resistance coefficients were calculated for \( v = 1.5-2.0 \) m/s. The evolution of \( C_D \) for equal Re numbers, however, was significantly higher \((p < 0.001)\) than the \( C_D \) evolution of the prone position during towing at the water surface. This implies that an even greater turbulence occurs, i.e., an increase in eddy resistance at the water surface.

![Figure 4](image)  
**Figure 4**  
Laminar and turbulent flow regions as a function of drag coefficient \((C_D)\) and Re numbers

The flow around a (human) body is and remains turbulent in all circumstances. According to hydrodynamic standards, eddy resistance and therefore total drag as a function of the small velocity range remains too high and will increase with a body that continuously changes its shape.

On the basis of the individual range of drag results (as a function of a limited velocity range) the favourable hydrodynamic influence that should be expected by a hydrodynamically ‘good’ range of Reynolds numbers \((2.10^5 < \text{Re} > 2.10^6)\) is also questionable. In other words, the small resistance variation that should accompany the Re numbers does not apply to human shapes and certainly not to shapes in permanent deformation (Ungerechts and Klauck 2006).

Multiple records cannot be explained by changes in constitutional morphology and the transient position differences of \( D_p \) are a clear indication that positioning is far more important than a ‘second skin’. Reducing \( D_p \) remains interesting only for the glide moments in starts and turns. The active swimming resistance is a total different matter.

One needs to consider that the swimming motion is a combination of complex transient positions with even more complex upper and lower limb movements synchronised by the trunk (Clarys 1985; Clarys and Cabri 1993) that will increase the turbulent resistance. It will totally disturb the boundary layer separation into no separation points at all. It becomes a ‘turbulent chaos’ with one single influencing relation, namely the quality of the executed swimming techniques. This technique can ‘maybe’ decrease wave making resistance but at all times there cannot be a frictional resistance because it simply cannot exist in that turbulent chaos. Creating a swimsuit concept based on an imitation of shark skin to explain drag decrease is no more, no less part of an imaginary reasoning for human swimming (Dean and Busham 2010; Oeffner and Lauder 2012). But it is a (very good)
promotional stunt of the different manufacturers. In short: swimmers whose shape changes substantially during the swimming stroke into a continuous body deformation cannot produce frictional resistance because the boundary layer and separations at theoc do not exist.

Considering that motion related morphology does not exist, considering that Dp nor Ds can explain the swimwear influence, the fact remains that during a relative short period the High-Tech swimwear was responsible for over 130 broken records.

At this point 2 issues deserve more attention: a) the manufacturers reference to ‘muscle compressing’ and ‘oscillation reducing’; and b) the swimmers reference that the High-Tech suits feel as a second skin, e.g. a full body condom (quote German newspaper ‘Der Tagesspiegel’).

Both the manufacturer statement and the swimmers proprioception are correct. The compression effect is confirmed by van Geer et al. (2012) while recent studies on body mechanics of fasciae structures linked to the skin have completed the kinesiological and anatomical knowledge of muscular segmental and visceral strength. Fascia is a tissue whose importance has long been neglected. However, as our body of research has expanded, it is now understood that fascia is critically important to the structure and function of the musculoskeletal system. It might not be long before the term musculoskeletal system is replaced by the term myofascioskeletal system (Muscolino 2012).

Fascia is a fibrous connective tissue that wraps and envelopes our body, providing a pervasive web that interconnects all tissues of that body. Simply put, fascia is responsible for the cohesiveness and function of our body forming myokinetic chains enforced by the skin.

Adipose and other cells occupy the spaces in between to provide protection of the passage ways for nerves, blood and lymphatic vessels (Clarys 1979; Huijing et al. 1986; Muscolino 2012). The superficial fascia is more adherent to the skin than it is to the deeper fascia tissue. This allows for greater motion and force production of the underlying fascia and musculature. A full body High-Tech ‘compressing’ suit will enhance the positive effect of the skin + superficial fascia combination. The myofascial force transmission and the active fascial contractility will increase and influence musculoskeletal dynamics. (Huijing and Baan 2003; Schleip et al. 2005). It is therefore the most probable and only explanation for the broken records. The proprioception of the athletes concerned was the closest to the probable reality.

**Epilogue**

Does the High-Tech suit give swimmers an unfair advantage? ... Why ban High-Tech swimwear which facilitates movement only. In cycling the aerodynamic outfit and bike design improves performance at a level of seconds and even allows for ‘minutes’ over distance. Nor the High-Tech swimwear, nor the aerodynamics hardware in cycling do overrule the individuals training and performance effort. Dubious science or discriminating morality at Olympic level?

**Conclusion**

The High-Tech swimsuit advantages cannot be explained by hydrodynamics due to the turbulent chaos created by a continuous body deformation during the swimming motion.

Both in motion and glide periods water temperature and alignment (or technique) are more discriminating than morphology.

The High-Tech full body swimsuit enforces both the skin the connected fasciae, suggesting an improved myofascial force transmission.

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The effect of feet placement during the wall contact phase on freestyle turns

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¹Loughborough University, Loughborough, England

Keywords: swimming, freestyle turns, pressure mat

Abstract

A waterproofed pressure mat was used to analyse the wall contact phase of freestyle turns by 34 university swimmers to determine the variables on the wall that effect turning performance. Data was analysed as a group of athletes and then divided by gender to see if males and females used the same approach to turning technique with different anthropometry. Foot position and orientation with relation to the surface of the water, wall contact time and maximum depth were related to the criterion measure of 5m Round Trip Time (RTT). Within the group that was tested the only significant correlation (p=0.05) with turn performance during the wall contact phase was the tuck index (0.330). When the sample was divided by the gender of the swimmer the foot width and orientation were significantly related to the 5m RTT for the males while the Wall Contact Time (WCT), foot height, foot width and tuck index were related to female turn performance. Rotation time, height, mass and tuck index were related with successful turning while future testing should investigate the turning performance freestyle specialist swimmers to determine the impact of foot placement.

Introduction

Turn performance has been monitored both in a training and competition environment and includes various phases such as the approach, rotation, wall contact, push off, underwater and swimming segments (Lyttle & Benjanuvatra 2007). Freestyle turns have been investigated by a number of researchers with the instrumentation during the wall contact phase limited to force platforms and video cameras (Blanksby et al. 1998, 1996, 1995; Cossor et al. 1999; Lyttle & Mason 1997; Lyttle et al. 1999; Nicol & Kruger 1979; Pereira et al. 2011; Prins & Patz 2006; Puel et al. 2010, 2012; Takahashi et al. 1983).

A limitation with the use of force platforms for analysis is the inability to determine the position and contribution of individual legs to the overall turn performance. Previous research has discussed the development of turn analysis systems that incorporate the use of a pressure mat (Chakravorti et al. 2012a, 2012b; Cossor et al. 2012; Webster et al. 2011). Each of these studies proved the concept of pressure mats and bespoke software for turn analysis with a limited number of subjects.

Video at major international competitions has shown that there are two techniques that are used by elite swimmers when contacting the wall. The first includes a faster rotation around the transvers axis with the feet contacting the wall so that the toes are pointing towards the surface of the water where the orientation is referred to as 0°. The other technique includes an additional rotation of the body along the medial axis when approaching the wall so that the feet contact the wall when the toes are positioned towards the side walls creating an orientation of 90°. The purpose of this study was to evaluate foot orientation as a contributor of performance in freestyle turns.

Methods

An integrated approach to the analysis of swimming turns was used that included the use of three underwater cameras (Sony HQ2) and a waterproofed flexible pressure sensor mat (XSENSOR model IX500:40:64:02). The design of the pressure mat has been discussed previously by Cossor et al. (2012) including the detail of the 2560 individual sensing elements within the active area of the mat.

The pressure mat was connected to a laptop that captured the pressure data at 100Hz for further analysis. One of the cameras was attached to a tripod and viewed the rotation phase of the turn...
above the water while the two other cameras were attached to poles that were 2m and 4m from the end of the pool and at a depth of 1m below the surface of the water. A representation of the testing set up is shown in Figure 1 with the approximate location of the equipment used.

Figure 1  Turn testing set up with a pressure mat and three video cameras

Thirty-four university swimmers completed three maximal effort freestyle turns with sufficient rest between each trial to ensure a full recovery. The average mass was 81.16 ± 6.51kg for the males and 68.17 ± 4.60kg for the females. Standing height was 1.86 ± 0.06m for the males and 1.73 ± 0.05m for the females as displayed in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Number of trials</th>
<th>Mass (kg)</th>
<th>Standing height (m)</th>
<th>Trochanter height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>65</td>
<td>81.16 ± 6.51</td>
<td>1.86 ± 0.06</td>
<td>0.95 ± 0.04</td>
</tr>
<tr>
<td>Females</td>
<td>34</td>
<td>68.17 ± 4.60</td>
<td>1.73 ± 0.05</td>
<td>0.90 ± 0.02</td>
</tr>
</tbody>
</table>

Analysis measures included the 5m Round Trip Time (RTT), foot placement and orientation on the wall, peak pressure, Wall Contact Time (WCT), and maximum depth of the hip after leaving the wall. Time and velocity during the last hand entry, feet leaving the wall and the first underwater kick were also recorded using the SwimTrack© software as described by Cossor et al. (2012).

The centre of the swimmer’s head was used to calculate the RTT during the approach to the wall and return to the same 5m distance. It was possible to measure the horizontal and vertical position of each foot during the wall contact phase due to the large number of sensing elements within the mat so that each calculations could be made by multiplying the cell number for the sensing element where contact occurred by the size of the cell (12.7 x 12.7mm). The method used to calculate the orientation between the centre of each foot when contacting the wall was described in Cossor et al. (2012). Peak pressure and wall contact time was manually calculated using the XSensor software.
Instantaneous velocity at a set point was calculated using data from the previous two frames as well as the next two frames of video operating at 25 frames per second and known distances at each of these points using the calibration process prior to each testing session.

**Results**

Only those trials where both feet came into contact with the sensing area on the pressure mat were used for analysis purposes, which resulted in 99 of the 102 turns being analysed. Mean and standard deviations for the 5m RTT, WCT, foot width, foot height, orientation and tuck index are presented in Table 2. The average turn time for males (4.66s) was much faster than for the females (5.39s) within the group whilst the wall contact time of 0.31s was the same for all participants. Standard deviations reported for the foot width and foot height showed large differences within the subject population as did the orientation of the feet on the wall.

Tuck index is a measure reported in previous literature (Blanksby et al. 1996; Cossor et al. 1999; Prins and Patz 2006) where the distance of the greater trochanter to the wall is measured during wall contact. This measure is then divided by the swimmer’s trochanteric height to provide the tuck index value with smaller values indicating a bent knee position and larger values representing straighter legs when contacting the wall.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Mean and standard deviation data for variables during the wall contact phase and the 5m RTT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 m RTT (s)</td>
</tr>
<tr>
<td>Males</td>
<td>4.66 ± 0.22</td>
</tr>
<tr>
<td>Females</td>
<td>5.39 ± 0.23</td>
</tr>
<tr>
<td>Combined</td>
<td>4.91 ± 0.41</td>
</tr>
</tbody>
</table>

Pearson Product Moment Correlations showed significant (p<0.05) relationships between the criterion measure 5m RTT and (i) rotation time (0.312), (ii) height (-0.718), mass (-0.739), and (iv) tuck index (0.330). Wall contact time, foot width, foot height, orientation, and maximum depth did not significantly correlate with freestyle turn performance when the data was analysed as a complete group. Data was then separated by gender with the significant relationships (p<0.05) shown in Table 3.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Significant (p=0.05) Pearson Product Moment Correlations with wall contact phase variables and the 5m RTT criterion measure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WCT (s)</td>
</tr>
<tr>
<td>Males</td>
<td>-0.275</td>
</tr>
<tr>
<td>Females</td>
<td>0.403</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
</tr>
</tbody>
</table>

The only parameter that provided a significant correlation for the wall contact phase and the 5m RTT when the subjects were combined into one group was the tuck index. This would suggest that both the males and females use a similar knee angle position when contacting the wall so that the hips are at approximately the same distance from the wall relative to their height.

**Discussion**

Observations of turning performance during the 2012 Olympic Games highlighted two different foot positions on the wall during the freestyle turn. The first was to have the toes of the feet pointing towards the surface of the water while the second had the feet rotated between 45 and 90° when contacting the wall. As such the purpose of the research was to determine if the placement of the feet on the wall impacted on the turning performance of elite swimmers. It was not possible to
measure this information using traditional force platforms so a waterproofed pressure mat was developed that enabled each foot to be measured separately. Data from this research showed that the orientation of the feet was significantly related to the turning performance for the male subjects but not the females although the standard deviations were large for both genders.

Marinho et al. (2010) found an effect on the depth of the swimmer during the glide phase after turning to reduce drag although the maximum depth of the swimmers in this study did not impact on the total turn time. The position of the hips in relation to the feet during wall contact determines the depth of the swimmer during the underwater phase – if they are even then the body will be parallel to the surface of the water. When the feet are higher than the hips then the swimmer will travel towards the bottom of the pool whereas the opposite is true when the position of the hips and feet are reversed as the swimmer leaves the wall. There may also be individual differences observed within the elite population so case studies may be more appropriate in the future.

In research examining 8 elite female athletes performing freestyle turns where the 3m RTT was used as the criterion measure, Puel et al. (2010) suggested that the glide duration and maximal horizontal force were the variables related to improved turning performance. As the swimmers left the wall in the current study there was a positive correlation with the timing of the first kick (0.599) and negative correlation with the velocity at which this kick occurred (-0.226) with the 5m RTT. These results indicated that the swimmers with a faster 5m RTT held their streamlined position for a longer period of time prior to commencing the first kick in the underwater phase and this enabled their velocity to decrease to a level that was similar to their kicking speed.

More comprehensive measures of the body position and the drag acting on the body during this phase of the turn will provide a more detailed understanding of the underwater phase and should be investigated in future research.

Whilst the group of swimmers used within this study were experienced and trained for a minimum of 8 sessions per week, they were not all freestyle specialists and the results may have differed with a smaller sample size who competed in freestyle events on a regular basis. The large standard deviations observed in the foot width, foot height and orientation measures within the group suggest that there was not a consistent trend of foot placement during the wall contact phase of the turn.

There were also large standard deviations within the subject group used indicating large variations in turning technique. Future research could look to measure correlations for each individual where more trials were monitored (8-10) for an improved interpretation of the relationship between the wall contact phase and 5m RTT.

**Conclusions**

The group of swimmers used in the current study showed similar trends to previous research (Blanksby et al. 1998; Cossor et al. 1999) where turn time was related to the height and mass of the individual. There were no significant relationships with the placement and pressure of each foot during the wall contact phase and the 5m RTT when analysed as a complete group. Significant relationships during the wall contact phase of the freestyle turn were observed when the males and females were analysed separately.

Future research should examine the individual foot position on the wall during tumble turns for freestyle specialist swimmers to make a more accurate assessment of the impact of feet placement on successful turn performance as well as use case studies within the elite population.

**References**


Should the gliding phase be included in the backstroke starting analysis?

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Keywords: biomechanics, kinematics, hip velocity-time curve, swimming, dorsal start, starting variants

This study aimed to characterise the underwater phase of the backstroke start. Nine highly trained backstroke swimmers performed a maximal 3x15 m of the starting variant with feet parallel and partially emerged and the highest horizontal handgrip. The best 15 m trial was selected for each swimmer. Motion capture system tracked right side markers. Each individual velocity curve was normalised from the immersion until the beginning of the upper limbs propulsion. The velocity at full immersion and at five critical instants of the 1st undulatory underwater cycle was assessed. After the full immersion, swimmers performed a downward kick with lower horizontal and resultant velocity than those displayed at full immersion (1.15±0.18 vs. 2.09±0.26 and 1.62±0.36 vs. 2.39±0.33 m/s, respectively). The transition to the 1st upward kick generated greater horizontal, vertical and resultant velocity than those noted at 1st downward kick (1.79±0.18 vs. 1.15±0.18, -1.23±0.51 vs. -1.0±0.34, 2.14±0.23 vs. 1.62±.36 m/s, respectively). Compared to the 1st upward kick, swimmers displayed lower horizontal, vertical and resultant velocity at the 1st part of the transition from the 1st up to the 2nd downward kick (1.67±0.15 vs. 1.79±0.18, -0.29±0.21 vs. -1.23±.51, 1.73±0.13 vs. 2.14±0.23 m/s, respectively). Lower horizontal and resultant velocity was observed at the 2nd downward kick compared to the 2nd part of the transition from the 1st up to 2nd downward kick (0.96±0.22 vs. 1.68±0.14, 1.14±0.30 vs. 1.70±0.15 m/s, respectively). Subsequently to the full immersion, a downward kick was performed implying the swimmers’ deceleration, which was minimised by continued undulatory underwater cycles. These findings highlighted the absence of the gliding phase during the backstroke start.

Introduction

The swimming start is accepted as an important part of short and middle distance swimming events, and, if performed effectively, might decide the swimmer’s classification (de Jesus et al. 2011). For instance, 15 m after the start, the second-placed at men’s 100 m backstroke at Barcelona 2013 Swimming World Championships was 0.20 s slower than the winner, and the final race time difference was 0.19 s. The importance of the start is emphasised further by the observation that the differences between the individual 15 m performances of international level swimmers might correspond to 0.30 s (c.f. Vantorre et al. 2010).

The starting performance is usually defined by the period between the starting signal until the swimmer’s head reaches 15 m (e.g. Vantorre et al. 2010), and it is composed of several phases, namely block/wall, flight, entry, underwater and swimming phases (Vantorre et al. 2010). The underwater phase of the start is divided into the glide and underwater undulatory swimming (Maglischo 2003; Vantorre et al. 2010). The glide corresponds to the period between swimmer’s full immersion and beginning of lower limbs propulsion (Vantorre et al. 2010), and the undulatory underwater swimming is defined between gliding ending and beginning of upper limbs propulsion (de Jesus et al. 2012; Vantorre et al. 2010).

Several authors studied in detail the underwater phase of ventral starts (e.g. Vantorre et al. 2010), while minor attention has been paid to the backstroke starting technique. Cohen et al. (2011) studied one dorsal undulatory underwater swimming cycle using numerical method, while de Jesus et al. (2012) analysed kinematics of the four initial and last four undulatory cycles of different backstroke starting variants. In both studies, authors have not attempted to analyse the underwater phase
movements performed after full immersion. According to Maglischo (2003), the underwater phase of backstroke start displays a well defined gliding period, although it was described after descendent swimmer's actions. Hohmann et al. (2008) described undulatory underwater kicking movements immediately after swimmer's immersion. In fact, since backstroke swimmers have to perform upper, trunk and lower limbs movements to decrease the vertical displacement after backstroke start full immersion (Green et al. 1987), it might be speculated that propulsive actions occur as soon as swimmers enter the water, evidencing the lack of a conventional gliding phase at backstroke start. This study aimed to characterise the underwater phase kinematics of one of the most used backstroke starting variants.

**Methods**

After a month of backstroke starting training period, 9 highly trained backstroke swimmers (22.22 ± 6.37 yrs, 1.78 ± 0.04 m, 72.67 ± 10.85 kg) performed three 15 m maximal trials of the backstroke starting variant with feet parallel and partially emerged and the highest horizontal handgrip with 3 min resting. Starting signals were produced through a starter device (ProStart, Colorado Time System, USA). The best trial in terms of 15 m performance of each swimmer was selected for analysis.

Synchronised to the starting device, an optical motion capture system was used with six underwater cameras (Oqus, Qualisys AB, Sweden), five lateral and one obliquely positioned regarding to the swimmer’s plane of movement. Lateral cameras were alternatively placed at 0.10 m below the water surface and at the swimming pool bottom and were 0.5, 5, 10, 15 and 20 m away from the starting wall. The oblique camera was positioned 20 and 5 m away from the frontal and lateral pool wall, respectively. The camera lenses were targeted to the swimmer’s trajectory and registered the swimmers’ movements from the full body immersion until the beginning of the upper limbs propulsion.

The underwater calibration was performed with a static calibration frame (positioned 5 m further from the pool wall) to create the virtual origin in the 3D environment and a wand calibration was used to perform the dynamic calibration, which covered the expected performance volume. Figure 1 shows the six cameras positioning and the covered calibration volume.

![Figure 1 The six cameras positioning](image)

A short data acquisition was performed prior to the backstroke start recordings, to determine the water surface position and orientation relative to the origin of the calibration frame. As the underwater motion analysis imposes several unique obstacles such as insufficient illumination and reflex, and these adversities reduce the calibration accuracy, markers exposure time and threshold were adjusted according to the different environmental conditions.
The cameras tracked the swimmers’ right hip reflective marker, and the horizontal, vertical and resultant hip velocity-time curves were processed using Qualisys Track Manager (Qualisys AB, Sweden). A referential transformation was applied to the original calibration referential in order to align it with the water level at the starting block, setting this point as the new referential origin. Each individual velocity time-curve was smoothed using a low pass digital filter, and subsequently normalised in time from the hallux immersion until the beginning of the upper limbs propulsion using a custom-designed software program (MatLab, 7.11.0 R2010b, MathWorks Inc., USA). The velocity at full immersion and at five critical instants of the 1st undulatory underwater kicking cycle was assessed at each normalised individual curve. These velocity-time curve instants corresponded to the minimum velocity achieved during the 1st downward kicking, the maximal velocity during the 1st upward kicking, the minimum velocity during the 1st part of the transition from the 1st upward to the 2nd downward kicking, the maximal velocity during the 2nd part of the transition from the 1st upward to the 2nd downward kicking, and the minimum velocity achieved during the 2nd downward kicking.

Figure 2 presents the respective critical instants studied, which are represented by stick figures on the mean resultant hip-velocity to time curve of the nine swimmers.

Paired sample t-test was used to determine the effects caused by the critical instant on the velocity time-curve profile (P-value ≤ .05). The effect size was calculated based on Cohen’s (1988) criteria. It was considered small if 0≤|d|≤0.2, medium if 0.2≤|d|≤0.5, and large if |d|>0.5.

**Results**

Table 1 displays the mean (± s) values of horizontal, vertical and resultant swimmers’ hip velocity at each critical instant analysed, with P-value and effect size (d) reported for the comparisons between the respective critical instants. Compared to the full immersion, swimmers displayed shorter horizontal and resultant velocity with a large magnitude effect size; however, non-difference was observed for the vertical component, with moderate effect size. During the 1st upward kicking, greater horizontal, vertical and resultant velocity was generated than those noted during the 1st downward kicking, with large effect size. Compared to the 1st upward kick, swimmers displayed lower
horizontal, vertical and resultant velocity during the 1st part of the transition from the 1st up to the 2nd downward kick, with large effect size. Difference was not noted between the 1st and 2nd part of the transition from the upward to the downward kicking for the horizontal, vertical and resultant velocity, with small, large and medium effect size, respectively. Lower horizontal and resultant velocity was observed during the 2nd downward kick compared to the 2nd part of the transition from 1st up to 2nd downward kick, with large effect size. Greater downward vertical velocity was displayed during the 2nd downward kick compared to 2nd part of the transition from 1st up to 2nd downward kick, with large effect size.

Table 1  Mean (± sd) of horizontal, vertical and resultant swimmers’ hip velocity at each critical instant analysed, with P-value and effect size (d) reported for each comparison between critical instants.

<table>
<thead>
<tr>
<th>Velocity (m∙s⁻¹)</th>
<th>Critical instants</th>
<th>Mean (± sd)</th>
<th>P-value</th>
<th>Effect size (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>SFIM</td>
<td>2.09±0.26</td>
<td>0.012</td>
<td>5.49</td>
</tr>
<tr>
<td></td>
<td>1st DWN KICK</td>
<td>1.15±0.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1st DWN KICK</td>
<td>1.15±0.18</td>
<td>0.008</td>
<td>-3.31</td>
</tr>
<tr>
<td></td>
<td>UPW KICK</td>
<td>1.79±0.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>UPW KICK</td>
<td>1.79±0.18</td>
<td>0.012</td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td>1st UP to DWN KICK</td>
<td>1.67±0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1st UP to DWN KICK</td>
<td>1.67±0.15</td>
<td>0.513</td>
<td>-0.04</td>
</tr>
<tr>
<td></td>
<td>2nd UP to DWN KICK</td>
<td>1.68±0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd UP to DWN KICK</td>
<td>1.68±0.14</td>
<td>0.008</td>
<td>4.40</td>
</tr>
<tr>
<td></td>
<td>2nd DWN KICK</td>
<td>0.96±0.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>SFIM</td>
<td>-1.16±0.30</td>
<td>0.77</td>
<td>-0.35</td>
</tr>
<tr>
<td></td>
<td>1st DWN KICK</td>
<td>-1.00±0.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1st DWN KICK</td>
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<td>0.05</td>
<td>0.81</td>
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<tr>
<td></td>
<td>UPW KICK</td>
<td>-1.23±0.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>UPW KICK</td>
<td>-1.23±0.51</td>
<td>0.01</td>
<td>-2.20</td>
</tr>
<tr>
<td></td>
<td>1st UP to DWN KICK</td>
<td>-0.29±0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td>0.09</td>
<td>-0.77</td>
</tr>
<tr>
<td></td>
<td>2nd UP to DWN KICK</td>
<td>-0.01±0.43</td>
<td></td>
<td></td>
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<tr>
<td></td>
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<td>-0.01±0.43</td>
<td>0.01</td>
<td>1.38</td>
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<tr>
<td></td>
<td>2nd DWN KICK</td>
<td>-0.56±0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resultant</td>
<td>SFIM</td>
<td>2.39±0.33</td>
<td>0.01</td>
<td>3.40</td>
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<tr>
<td></td>
<td>1st DWN KICK</td>
<td>1.62±0.36</td>
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<td></td>
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<tr>
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<td>1st DWN KICK</td>
<td>1.62±0.36</td>
<td>0.01</td>
<td>-1.78</td>
</tr>
<tr>
<td></td>
<td>UPW KICK</td>
<td>2.14±0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>UPW KICK</td>
<td>2.14±0.23</td>
<td>0.008</td>
<td>2.42</td>
</tr>
<tr>
<td></td>
<td>1st UP to DWN KICK</td>
<td>1.73±0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1st UP to DWN KICK</td>
<td>1.73±0.13</td>
<td>0.51</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>2nd UP to DWN KICK</td>
<td>1.70±0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd UP to DWN KICK</td>
<td>1.70±0.15</td>
<td>0.008</td>
<td>3.06</td>
</tr>
<tr>
<td></td>
<td>2nd DWN KICK</td>
<td>1.14±0.39</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: SFIM (swimmer’s full immersion), 1st DWN KICK (first downward kicking); UPW KICK (upward kicking); 1st UP to DWN KICK (first part of the transition from the 1st upward to the 2nd downward kicking); 2nd UP to DWN KICK (second part of the transition from the 1st upward to the 2nd downward kicking); 2nd DWN KICK (second downward kicking).

Discussion

According to some previous reports considering the ventral (Vantorre et al. 2010) and backstroke starting technique (Maglischo 2003), the underwater phase has been divided into gliding and underwater undulatory swimming. Swimmers have been recommended to spend ~1s gliding in a hydrodynamic body position before the beginning of the lower limbs propulsion (Maglischo 2003; Vantorre et al. 2010). Contradictorily, Hohmann et al. (2008) described the entry and gliding phases of backstroke starting technique including downward and upward lower limbs movements. In
accordance to Green et al. (1987), after the backstroke starting entry phase, swimmers have to perform trunk, upper and lower limbs movements to alter the vertical downward displacement. These unclear starting phases’ definitions hamper an effective communication among biomechanists, coaches and swimmers, implying failure to apply research findings. Therefore, this study proposed to analyse the underwater phase kinematics of a commonly used backstroke starting variant, providing further insights into the underwater phases’ definition used for research and practical applications. The current findings indicated that subsequently to the full immersion, a downward kicking is performed implying a swimmers’ deceleration magnitude reduction, and specially an antero-posterior deceleration reduction, which is further minimised by immediately continued undulatory underwater swimming cycles (Figure 2). Thus, these results newly evidenced the absence of the gliding phase during the backstroke start, as we have previously hypothesised.

Despite the high horizontal and resultant velocity achieved immediately after the starting entry phase (Figure 2), the backstroke swimmers were unable to sustain such velocities in a hydrodynamic position due to the pronounced vertical displacement occurring during immersion. The swimmers generate a high tendency toward rotation during the flight for the backward swing movement and subsequently hole water entry (Maglischo 2003), which must be controlled as soon as the swimmer’s hip immerge (Green et al. 1987). Since the resultant velocity achieved immediately after the water immersion have been considered a determinant factor to reduce the backstroke starting time (de Jesus et al. 2011), coaches and swimmers should pay attention to minimise this velocity loss at the end of the downward and beginning of the upward kicking cycle. According to Maglischo (2003), swimmers who intend to perform longest undulatory underwater swimming phase should allow the body to travel deeper into the water by gliding for a short time before the beginning of kicking movements. In opposition, swimmers performing shortest undulatory underwater swimming phase lift the upper limbs sharply and bring the lower limbs down in preparation for the kicking movements almost immediately after the full immersion (Maglischo 2003). Based on these statements it has been suggested that backstroke swimmers may adopt different underwater starting phase profiles; however, in the present study and for the analysed starting variant, all swimmers performed a downward undulatory kicking after the full immersion, and continue the undulatory movement afterward, evidencing no gliding phase at all.

During the 1st downward undulatory underwater kicking, the vertical downward path is changed (Green et al. 1987; Maglischo 2003), but at the respective kick ending, and beginning of the upward kicking, the horizontal and resultant velocity achieved the minimum value. The largest projected frontal area (and consequently net drag force) when the knee attains maximum flexion were pointed out to create a large negative swimmers’ acceleration (Cohen et al. 2012). The negative acceleration in the resultant (Figure 2) and horizontal velocity components due to the 1st downward kicking was suddenly minimised by an upward undulatory swimming movement. In fact, stronger vortex rings and consequently greater trust generation were observed in the extension compared to the flexion kicking (Cohen et al. 2012). According to de Jesus et al. (2012), the first undulatory underwater swimming cycles displayed greater horizontal velocity than the last cycles. The downward vertical velocity during the 1st upward kicking was also greater than during the 1st downward kicking, which is due to the hip downward reaction to the torque produced by the lower limbs during upward movement.

The first part of the transition from the 1st upward to the 2nd downward kicking generated shorter horizontal, vertical and resultant velocity. Indeed, subsequently to the end of the 1st upward kicking, swimmers increase the respective frontal area and consequently the pressure drag (Cohen et al. 2012), hampering the forward displacement. In addition, vertical downward displacement is reduced since the greater torque seems to be generated previously to the first part of the transition from the upward to the downward kicking. The first and second part of the transition from the 1st upward to the 2nd downward kicking did not differ for horizontal, vertical and resultant velocity components, indicating that the streamwise forces are constant and close to neutral, meaning this is a recovery phase of the kicking cycle and has a minor effect on the velocity of the swimmer (Cohen et al. 2012). As the knee flexion continues until the maximum value, the frontal area increases (Cohen et al. 2012)
and negative acceleration is observed at the end of the undulatory underwater swimming cycle. In the present study, the three velocity components analysed presented shorter values than the 2nd part of the transition from the 1st to the 2nd downward kicking.

**Conclusion**

This is the first attempt to describe the underwater phase kinematics subsequent to a commonly used backstroke starting variant. The studies conducted in this starting phase are obsolete and scarce, and have not explained consistently the underwater sub phase’s definition. In the present study, after the full immersion, a downward kick was performed implying the swimmers’ negative acceleration. This detrimental effect on horizontal and resultant velocity components were minimised by continued undulatory underwater cycles, evidencing the absence of the gliding phase at backstroke start. Further biomechanical studies are required to perform a more detailed analysis of the underwater starting phase when backstroke swimmers perform different starting variants. Based on the current findings, coaches and swimmers should minimise the maximal knee flexion at the 1st downward kicking, which reduces the projected frontal area and resistive drag.

**Acknowledgments**

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**References**


Effect of different protocol step lengths on swim efficiency and arm coordination in front crawl swimmers

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Keywords: kinematics, efficiency, index of stroke coordination, front crawl

Abstract

This study aimed to compare incremental and intermittent protocols with different step lengths to observe eventual changes in technique related parameters. Eleven national level swimmers (20.4±2.5 yrs, 1.80±0.06 m, and 74.1±4.12 kg) performed three variants of a front crawl incremental and intermittent protocol (7x200, 7x300 and 7x400 m) until exhaustion, with increments of 0.05m/s and 30 s rest intervals between step and 48h between each protocol variant. Swimmers were videotaped in the sagittal plane at the 7th lap of each step of each variant, using a dual media set-up. APASystem was used to obtain the swim efficiency and arm coordination parameters: (i) intracycle speed variation of the horizontal swimmer’s hip displacement (IVV); (ii) difference between the maximal and minimal horizontal hip velocity within the stroke cycle (dv); (iii) propelling efficiency (np) and index of coordination (IdC). Comparison among the three variants of the incremental protocol did not show differences for swim efficiency and arm coordination. The results for IVV, dv, np, IdC for 7x200, 7x300 and 7x400 m were, respectively: (i) 0.16 to 0.18, 0.21 to 0.23, 0.20 to 0.21; (ii) 1.08 to 1.12, 1.05 to 1.26, 0.80 to 0.95; (iii) 1.47 to 1.78, 1.52 to 1.89, 1.54 to 1.80; (iv) -7.6 to -1.89, -8.41 to -0.18, and -7.37 to -0.14. All the comparisons for a Mean Rank > 1.50 and a P value > 0.05. Since there were no differences between the three protocol variants, the one with shortest step length (i.e. 200-m) should be adopted due to practical and pragmatic reasons.

Introduction

Traditionally, incremental protocols have been implemented without stopping the exercise, and continuously increasing the intensity between steps. However, in swimming, the implementation of short resting intervals between steps is required, since the swimmer can receive proper feedbacks, and researches can collect capillary blood samples to assess relevant energetic outcomes as the lactate kinetics and energy cost of locomotion and, eventually, control swimming intensity through the perceived exhaustion (Fernandes et al., 2005). In 2011, Fernandes and co-authors, comparing the effect of different variants (200 vs 300 vs 400 m) of an incremental protocol on physiological parameters, observed that the velocity and the heart rate corresponding to individual anaerobic threshold, the blood lactate concentrations and heart rate maximal values were similar among protocol’s variants (Fernandes et al., 2011). The only exception observed was the higher blood lactate values at individual anaerobic threshold in the 200 and 300 m compared to 400 m variant. Focusing mainly at energetics, Fernandes et al. (2012), reported that the 200 and 300 m variants accounted for higher percentage of oxygen consumption plateau incidence and higher maximal oxygen consumption values compared to the 400 m step protocol. From an energetic point of view, these authors have concluded that the 200 m variant is the most suitable to be used, as it decreases the logistic time need to individually assess swimmers, without a significant impact on validity and accuracy of the data collected.

Despite the previous statements, the intermittent incremental protocols have also been analysed to assess the respective biomechanical and motor control parameters. In fact, several technique variables are particularly related to the swim efficiency (e.g. propulsive efficiency and intracycle speed variation) (Barbosa et al., 2008; Komar et al., 2012) and inter limb-coordination (e.g. index of coordination) (Figueiredo et al., 2013). According to Fernandes et al. (2011), to select a protocol variant with short step length it is necessary that its durations would not affect significantly...
energetics, kinematics, and inter-limb coordination, but until now, no research comparing swimmer’s efficiency biomechanics and coordination during an intermittent incremental protocol with different step lengths was done. So, the purpose of this study was to compare three variants of an intermittent incremental protocol to observe eventual changes in technique related parameters. It was hypothesised that there are no significant differences in swim efficiency and inter-limb coordination variables induced by shorter step lengths, and for pragmatic reasons, a shortest step distance should be selected.

**Methods**

Eleven trained swimmers (20.4±2.5 yrs, 1.80±0.06 m, and 74.1±4.12 kg) voluntarily participated in the study. Swimmers were completely informed about the procedures and demands of the study and signed a written informed consent, approved by the Institutional Ethics Committee. All subjects were familiarised with the testing procedure and equipments.

**Procedures**

All tests sessions took place in a 25 m indoor swimming pool, 1.90 m deep, with water temperature at 27.5°C. A standardised warm-up, consisting of 1000 m of aerobic swimming of low-to-moderate intensity, was conducted before each variant of the protocol. Using in water starts and flips turns, each participant performed, in randomised order, three variants of the front crawl intermittent incremental protocol until exhaustion (i.e., 7x200, 7x300 and 7x400 m). Each variant had increments of 0.05 m/s between steps and 30 s intervals. The predefined velocity of the last step was common to all variants, being established according to each swimmer personal best at 400 m front crawl swimming at that time of the experiments. Then, 0.05 m/s was successively subtracted, allowing the determination of the mean target velocity for each step of the incremental protocol (Fernandes et al., 2011). The swimming pace of each step was common to the three protocol’s variants and controlled through a visual pacer with flashing lights on the bottom of the pool (TAR. 1.1, GBK-Electronics, Aveiro, Portugal). In addition, elapsed time was measured with a stopwatch (Seiko chronometer) to assess the exact swimmer’s speed. A 48 h resting period was respected between each protocol variant and swimmers were asked to abstain from strenuous exercise during the testing period. All the subjects were able to perform 7x200 and 7x300 m, but only eight swimmers completed totally the 7th step of the 7x400 m protocol variant at the pre-defined velocity.

**Data collection**

Swimmers were videotaped in the sagittal plane for 2D kinematical analysis using a dual-media set-up, with both cameras (Sony, DCR-HC 42E, Nagoya, Japan) operating at a sampling frequency of 50 Hz, with 1/250 of digital shutter speed, fixed on a home-made designed support for video image recording (Vilas-Boas, 1996) and Figueiredo et al., 2013) (Figure 1).
This support was placed at the lateral pool wall, 12.5 m from the head wall, with cameras positioned 30 cm above and below the water surface and 7 m from the plane of movement. The underwater camera was placed in a waterproof housing (Sony SPK-HCB box) exactly below the surface camera. The swimmers were monitored when passing through a specific pre-calibrated space using a 2D calibration frame (6.3 m²) and images from both cameras were recorded independently.

Each camera recorded a space of 4.5 m long for the XX-axis, and participants wear specific anatomical markers on upper limbs and trunk. Synchronisation of the images was obtained through a pair of LEDs, fixed to the calibration volume and visible in the field of view of each camera.

Video images were manually digitised frame-by-frame (f=50 Hz) using a specific processing software (Ariel Performance Analysis System, Ariel Dynamics, USA) to obtain paired raw coordinates (x, y), and consecutive differentiation to obtain velocity. The analysis period comprised one complete stroke cycle in the 7th 25 m lap of each step of each protocol variant. To eliminate the possible effects of breathing on the studied variables, swimmers were instructed to perform non-breathing cycles when passing in the calibrated space. It was used the anthropometric model from Zatsiorsky and Seluyanov (1983) adapted by de Leva (1996), including nine anatomical landmarks from the upper body, the acromion, lateral humeral epicondyle, ulnar styloid process, third distal phalanx and prominence of great femoral trochanter. Six calibration points and DLT algorithm (Abdel-Aziz and Karara, 1971) were used for 2D reconstruction. The selection of a 5 Hz cut-off value for data filtering (with a low pass digital filter) had to be done according to residual analysis (residual errors vs cut-off frequency). Root Mean Square (RMS) reconstructions errors of six validations points on the calibration frame, which did not serve as control points, for the horizontal and vertical axes were, respectively: (i) 1.92 mm and 1.78 mm, representing 0.33 and 0.40% of calibrated space of above water; and (ii) 1.84 mm and 1.71 mm, representing, 0.38 and 0.43% of the calibrated space for underwater.

For the efficiency estimation, were selected the following parameters: (i) intracycle speed variation of the swimmer’s hip horizontal displacement (IVV), computed as the coefficient of variation of the instantaneous speed-time data for horizontal axis; (ii) difference between the maximal and minimal hip velocity within the stroke cycle (dv); (iii) propelling efficiency, as the ratio between average swimming speed squared and hand speed squared \( \eta_p = \frac{v^2}{u^2} \) (Toussaint et al., 2006).

To assess motor control, the index of coordination (IdC) was assessed by measuring the lag time between the propulsive phases of each arm, and expressed as the percentage of the overall duration of the stroke cycle (Chollet et al., 2000). Following these authors, the arm propulsive phases begins with the start of the hand’s backward movement and it ends at the moment where it exists from the water (pull and push phases), and the non-propulsive phase initiates when the hands releases from the water and ends at the beginning of the propulsive phase (recovery, entry and catch phases). For the front crawl technique, three coordination modes are proposed (Chollet et al., 2000): (i) catch up, when a lag time occurs between the propulsive phases of the two arms (IdC < 0%); (ii) opposition, when the propulsive phase of one arm starts and other arm ends its propulsive phase (IdC = 0%); and (iii) superposition, when the propulsive phases of the two arms are overlapped (IdC > 0%).

To determine the accuracy of the digitising procedure, two repeated digitisation of a randomly selected trial were selected, and the coefficients of repeatability with 95% agreements limits were calculated using Bland and Altman method for each variable of interest: (i) 0.00835 m/s [-0.0071 to 0.0098] for the horizontal hip’s velocity; (ii) 0.0022 m [-0.0026 to 0.0035] for hip’s horizontal displacement; and (iii) horizontal hand’s velocity 0.00996 m/s [-0.0091 to 0.0113]; (iv) 5.32° [-4.52 to 6.81] for trunk inclination.

**Statistical analysis**

Data distribution was screened, and a non-normal distribution was observed through scatter plots and formal test (Shapiro-Wilk). Swim efficiency and arm coordination values were presented as
median and interquartile range, and differences among the three protocol variants were tested for significance using the Friedman Multiple Comparison Test; the observed Z-scores for the dependent variable are based on positive or negative ranks, and significant differences are obtained if Z-score is in the [-1.96 to 1.96] interval. SPSS version 20.0 was used and statistical significance was defined for p < 0.05.

**Results**

Figure 2 presents the Median and interquartile range among the three protocol variants for efficiency parameters (Panel A, B and C) arm coordination (panel D). There were no variations in any of the selected dependent variable, i.e. IVV (p > 0.05; Z=2.019), dv (p > 0.05; Z=2.23), ηP (p > 0.05; Z=2.11) and IdC (p >0.05; Z=2.04).

![Figure 2](image)

**Discussion**

The aim of this study was to analyse the swim efficiency and arm coordination behaviours of three variants (200, 300 and 400 m) of a typical intermittent incremental protocol used for swimmer’s biophysical characterisation. For the selected dependent variables it was evidenced that distances of 200, 300 and 400 m did not induce differences on swim efficiency and arm coordination along the intermittent incremental protocol. Since the differences were not observed, the shortest step length (i.e. 200 m) should be adopted, as it reduces the time spent to collect the data and it is closer to the swimming distances used in competition (being more reliable for maximal performance).

Designing appropriate protocols for training control and evaluation of swimmers is a topic of interests of academics, sports analysts and coaches. Some claims and concerns have been addressed regarding the step duration needed to a given variable achieve a proper stabilisation, indistinctively if from energetics, biomechanics or motor control domains. However, despite the number of related publications available in the literature (cf. Fernandes and Vilas-Boas, 2012), there is no solid evidence of the step length to be used, especially regarding a swimming technique related evaluation. So,
understanding that to collect valid and accurate data the protocol design is one essential part of the control and evaluation process, Fernandes et al., (2011) and Fernandes et al., (2012) used different variants of an intermittent incremental protocol to assess energetic/physiological parameters, but recently, has appeared a growing interest in also evaluating some specific kinematics and motor control outcomes (Fernandes et al., 2012; Figueiredo et al., 2013; Komar et al., 2012). Notwithstanding the benefits of a selecting protocol with shorter step lengths for energetic evaluation (Fernandes et al., 2011), there is not a clear idea if different step lengths will influence the swimmer’s efficiency and motor control.

Since long time, a meaningful effort has been done by researchers to assess and understand the mechanisms underlying swimming efficiency (e.g. Barbosa et al., 2008; Toussaint et al., 2006) and the inter-limb coordination (Seifert et al. 2010). So, the present study selected those parameters aiming to highlight some technical issues for swimming performance, and, therefore, for control and evaluation, as well as for research purposes.

In the present study, we observed that, along the three protocol variants, the swim efficiency and arm coordination behaviors were similar to what have been reported in the literature for the incremental protocols with nx200 m. Some estimators suggest a change in the swimming efficiency (Seifert et al., 2010; Zamparo et al., 2005) and, IdC increases (Komar et al., 2012; Figueiredo et al., 2013). So, the replication (an essential part of the scientific activity) of the 7x200 m protocol was achieved.

Notwithstanding the novelty and pertinence of the current research, some limitations should be pointed out as it was performed a 2D kinematics assessment and, as swimming is a typical 3D motion movement (Figueiredo et al., 2013), some precaution should be taken when extrapolating this conclusions to some more detailed 3D kinematics. Moreover, to assess the swimmer’s displacement and velocity, it was considered the hip instead of the centre of mass, although nowadays is well established between .3% and .7% bias for the displacement and velocity of those anatomical landmarks, respectively (Fernandes et al., 2012). Finally, some new insights about the response of the motor control variables (e.g. the neuro-muscular activity) were neglected.

**Conclusions**

There are no meaningful kinematics and arm coordination differences between the three studied variants of the typical swimming intermittent incremental protocol. As training control and evaluation in elite sports is a research based on practice, most of the time done during regular training sessions or training camps, with a large number of athletes to be assessed, spending less time with such procedures is an advantage not only for researches but also for athletes and coaches. Therefore, a protocol with shorter step lengths (i.e. 200 m) can be adopted for both energetics and biomechanical characterisation since it will increase the logistics efficiency with a minimum impact in the data internal validity.

**Acknowledgments**

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**References**


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**Do fins alter spatiotemporal and physiological variables in front-crawl all-out effort?**

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**Keywords:** maximal swim, fins, masters

Fins are used in swimming training sessions for different purposes. The aim of this study was to identify and to compare the spatiotemporal and physiological parameters obtained with and without fins of 488 cm² area in maximal intensities of front crawl swimming. Eleven male swimmers performed two 50 m all-out in front crawl stroke, with (WF) and without fins (WOF). Swimming velocity (SV), stroke rate (SR), stroke length (SL), duration of stroke phases (A, B, C, D, propulsive and not propulsive on breathing side and opposite to breathing side) and index of coordination on both, breathing (IdC 1) and opposite of breathing side (IdC 2), number of kicks (NF), right feet deep (FRD) and left feet deep (FLD) were obtained by manuals time keepers and camcorders (60 Hz). Lactate concentration ([LA]) and perceived exertion (PE) were assessed. Fouts area were estimated. Fins increased 25% of the foot’s area compared to WOF. An increase in SV was observed when compared WP to WOF. With the use of fins athletes can perform greater propulsive forces due greater contact area with the water in comparison to the area of the foot, increasing (1) propulsive momentum, (2) volume of water displacement and (3) body alignment. Fins with area of 488 cm² may cause limited alterations in spatio-temporal parameters.
Introduction

Despite the scarcity of studies on the comparison between swimming with and without fins, it is known that fins use can increase efficiency of propulsion of the lower as well as the upper limbs (Zamparo et al. 2002; Matos et al. 2013) and swimming velocity (Pendergast et al. 2003; Matos et al. 2013), and can decrease physiological load (Zamparo et al. 2002; Matos et al. 2013) and stroke rate (Zamparo et al. 2005; Matos et al. 2013). However, there is still a gap in the literature regarding changes in caused by the use of fins regarding spatio-temporal and physiological variables such as stroke length, number of kicks per stroke cycle, foot depth, duration of stroke phases, index of coordination, as well as blood lactate concentration and perceived exertion during training series with fins. So this study tries to answer how do fins change spatio-temporal and physiological parameters of front-crawl stroke in maximal intensity?

The aims of this study were to compare average swimming velocity (SV), stroke rate (SR), stroke length (SL), kicks per stroke cycle (KC), foot depth (FD), stroke phase's duration (SD), index of coordination (IdC), blood lactate concentration [LA] and perceived exertion (PE) with and without fins of 488 cm² of area in front crawl stroke.

Methods

Participants

Eleven male masters swimmers (25.8 ± 5.5 years age; 75.2 ± 5.5 kg body mass; 177 ± 6.5 cm height; 388 ± 28.6 cm² estimated foot area; 4.5 ± 2.1 years in experience in swimming training with fins) performed two 50 m all-out trials, with and without fins. All participants signed a consentiment term and the study was approved by the Ethics Committee of the University where the study was carried out.

Protocol

Protocol was performed in two days, separated by 24h. In first day, anthropometric characteristics were obtained: body mass, height, upper arm span and estimated foot area. Foot area was estimated by the equations described by Du Bois and Du Bois (1916) and YU et al. (2009): Foot Area = (0.007184 * BM^{0.425} * HT^{0.725}) * k, where BM = body mass, HT = height, and k = constant related to the foot area (2.03%). In both days, swimmers performed 800 m in freestyle as warm-up, 50 m in front-crawl stroke, in maximal intensity, with a push-off from the wall, and 800 m in freestyle as warm-down. In first day, the 50 m was performed without fins (WOF), in the second day, with fins (WF). Before the WF, during the last 300 m of the 800 m in warm-up, swimmers wore the fins (Kpaloa®, semi-rigid, 488 cm² of area).

Data collection

To obtain SV, SR e SL a 10 m sector was defined in the center of the swimming pool to minimise the effects of swimmer’s impulse from the wall (Barbosa et al. 2008; Ribeiro et al. 2010). During the last 25 m of each 50 m, two trained researchers recorded the time (chronometers Casio, HS-30W) to perform 10 m and the time to perform three complete arm stroke cycles (one stroke cycle was considered as the time gap between two consecutives entries of the right hand in the water) using chronometers. SV was quantified by the quotient between 10 m and the time (in sec) to swim 10 m, swimmer head was the reference. SR was obtained using the time to perform three completes arm stroke cycles (T3C) at the 10 m zone. SL was assumed as the quotient between SV and SR.

Three synchronised camcorders (Sanyo, VPCWH1 XACTI TH1, operating at 60 Hz) were used to obtain above and underwater images from the sagittal plane of the swimmers in both conditions, WOF e WF. Two camcorders were positioned 30 cm under water surface, left and right pool wall, and one camcorder was positioned 10 cm above the water. The camcorders were fixed in two trolleys by a steel arm, 7.5 m from the swimmer. The trolleys were moved above trails by an experienced researcher, in the same velocity of each swimmer. KC, FD, SD, and IdC were quantified by the images analysis with the software Kinovea 0.8.15. Kicks per stroke cycle (KC) were obtained by digitalisation
of visual markers positioned in both lateral malleolus during a complete stroke cycle, both identified inside the 10 m zone in the recorded images. Foot depth (FD) was the maximal vertical distance of the markers from the water surface, for both, right (RFD) and left ankle (LFD). It was observed a straight position of the head, to avoid possible influence of the body roll in the FD. A vertical calibration frame (1 m) was used along the 10 m zone from the water surface. Pixels were transformed in meters to calculate FD. Stroke phase’s duration (SD) and index of coordination (IdC) were identified and calculated, relative a stroke cycle duration, as proposed by Chollet et al., (2000) and Seifert (2010), for breathing and non-breathing strokes. Stroke phases were identified in the frames: A (from the hand entry in the water until its position backward, non-propulsive), B (from the position backward until the position under the shoulder, propulsive), C (from the position under the shoulder until the hand releases from the water, propulsive) and D (from the hand releases from the water until its entry in the water, non-propulsive).

Blood lactate concentration [LA] was identified 3 min after both, WOF and WF trials, by a portable lactimeter (Accutrend Plus, Roche) with arterialised blood samples from the second fingertip. Perceived exertion (PE) was identified immediately after both trials with the Borg’s fifteen points scale (Borg 2000).

**Statistical analysis**

Means and standard-deviations were calculated. Shapiro-Wilk’s test and Student’s t tests for paired samples were applied in SPSS 17.0. A significance level of 0.05 was adopted for all tests.

**Results**

Table 1 shows all spatio-temporal results. Only SV in the WF trial was significantly higher when compared to the WOF trial (t(10) = -4.41; p = 0.01).
Table 1  Means and standard deviation of swimming velocity (SV, in m s\(^{-1}\)), stroke rate (SR, in Hz), stroke length (SL, in m), number of kicks per stroke cycle (NK, in kicks per cycle), right feet deep (RFD) and left feet deep (LFD, in meters), duration of stroke phases (A, B, C, D, propulsive—P and not propulsive—NP, all in %); side of breathing (B) and opposite to breathing (OB) and index of coordination of the breathing (IdC 1, in %) and opposite side of the breathing (IdC 2, in %) without (WOF) and with fins (WF), n = 11.

<table>
<thead>
<tr>
<th></th>
<th>WOF</th>
<th>WF</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>SV (m s(^{-1}))</td>
<td>1.57 ± 0.13</td>
<td>1.75 ± 0.10</td>
<td>0.01*</td>
</tr>
<tr>
<td>SR (Hz)</td>
<td>0.78 ± 0.13</td>
<td>0.84 ± 0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>SL (m)</td>
<td>2.05 ± 0.32</td>
<td>2.01 ± 0.21</td>
<td>0.71</td>
</tr>
<tr>
<td>NK (kick per cycle)</td>
<td>2.72 ± 0.46</td>
<td>2.68 ± 0.44</td>
<td>0.80</td>
</tr>
<tr>
<td>RFD (m)</td>
<td>0.44 ± 0.06</td>
<td>0.43 ± 0.10</td>
<td>0.74</td>
</tr>
<tr>
<td>LFD (m)</td>
<td>0.46 ± 0.11</td>
<td>0.41 ± 0.08</td>
<td>0.14</td>
</tr>
<tr>
<td>% Phase A (B)</td>
<td>32.85 ± 4.22</td>
<td>32.07 ± 7.58</td>
<td>0.75</td>
</tr>
<tr>
<td>% Phase A (OB)</td>
<td>30.32 ± 6.49</td>
<td>30.00 ± 6.23</td>
<td>0.86</td>
</tr>
<tr>
<td>% Phase B (B)</td>
<td>21.91 ± 4.90</td>
<td>22.31 ± 2.67</td>
<td>0.82</td>
</tr>
<tr>
<td>% Phase B (OB)</td>
<td>20.27 ± 4.68</td>
<td>21.94 ± 3.46</td>
<td>0.34</td>
</tr>
<tr>
<td>% Phase C (B)</td>
<td>24.46 ± 4.12</td>
<td>25.49 ± 4.64</td>
<td>0.32</td>
</tr>
<tr>
<td>% Phase C (OB)</td>
<td>26.09 ± 4.66</td>
<td>24.26 ± 3.85</td>
<td>0.21</td>
</tr>
<tr>
<td>% Phase D (B)</td>
<td>20.77 ± 6.66</td>
<td>19.05 ± 6.55</td>
<td>0.48</td>
</tr>
<tr>
<td>% Phase D (OB)</td>
<td>23.30 ± 4.37</td>
<td>23.71 ± 4.54</td>
<td>0.80</td>
</tr>
<tr>
<td>% Phase P (B)</td>
<td>46.37 ± 7.58</td>
<td>47.85 ± 5.92</td>
<td>0.39</td>
</tr>
<tr>
<td>% Phase P (OB)</td>
<td>46.37 ± 7.71</td>
<td>46.28 ± 5.70</td>
<td>0.96</td>
</tr>
<tr>
<td>% Phase NP (B)</td>
<td>53.62 ± 7.58</td>
<td>52.14 ± 5.92</td>
<td>0.39</td>
</tr>
<tr>
<td>% Phase NP (OB)</td>
<td>53.62 ± 7.71</td>
<td>53.71 ± 5.70</td>
<td>0.96</td>
</tr>
<tr>
<td>IdC 1</td>
<td>-0.46 ± 7.30</td>
<td>-2.80 ± 8.91</td>
<td>0.39</td>
</tr>
<tr>
<td>IdC 2</td>
<td>-3.15 ± 11.38</td>
<td>-7.02 ± 8.00</td>
<td>0.11</td>
</tr>
</tbody>
</table>

* significant difference

[LA] and PE were similar for both conditions, WOF and WF, as shown in Table 2.

Table 2  Means and standard-deviation of [LA] (mmol l\(^{-1}\)) and PE in 50 m WOF and WF trials, n = 11

<table>
<thead>
<tr>
<th></th>
<th>WOF</th>
<th>WF</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>[LA] (mmol l(^{-1}))</td>
<td>9.64 ± 2.36</td>
<td>9.75 ± 2.45</td>
<td>0.84</td>
</tr>
<tr>
<td>PE</td>
<td>18.82 ± 1.25</td>
<td>19.18 ± 0.87</td>
<td>0.21</td>
</tr>
</tbody>
</table>

**Discussion**

Values of SV, SR, SL, and duration of stroke phases found in this study were similar to those previously reported (Castro and Guimarães 2010; Chollet et al. 2000). No study was found regarding NK and FD values. IdC values were always negatives, indicating a catch-up model, but the great standard-deviation found for IdC in both situation, WOF and WF, indicates a great variability in the coordination adopted by the swimmers (Seifert 2010).

The chosen fins used in this study had area 25% greater than the mean foot area (from 388 ± 28.6 cm\(^{2}\) to 488 cm\(^{2}\)), which was fewer than 108 to 309% of other studies with fins (Zamparo et al. 2002, 2005, 2006). These fins are mostly used in swimming training rather than larger fins, and the mains objectives in the swimming training are to increase SV by neural adaptations, mainly by increase in SR and motor coordination, as assisted velocity method, as proposed by Bompa (2009) and increase front-crawl stroke technique, mainly by better body position. In this study, maximal SV was greater with fins, but SR was not significantly greater, just the sufficient to increase SV. The SV increase could be explained by: (1) greater propulsive forces from the fins due to the larger contact area with the
water in comparison with the area of the foot. Fins allow increase impulse, shifting greater water volume, and (2) better body alignment provided by the fins and the increase in speed. The more horizontal the body, better is the hydrodynamic position and lower the drag.

Similar results of stroke rate (SR), stroke length (SL), kicks per stroke cycle (KC), foot depth (FD), stroke phase’s duration (SD), and index of coordination (IdC) indicate that fins which are have are until 25% greater than foot area were not able to increase front-crawl stroke technique. It must be observed that swimming training with fins is not performed with fins as those studied by Pendergast et al., (2003) and Zamparo et al. (2002, 2005, 2006) and the maximal intensity used in this study is not a intensity regularly used in swimming training sessions to increase technique.

In both situations, WOF and WF, physiological parameters (LA and PE) indicate that 50 m trials were performed under similar intensity and fins were not able to modify anaerobic contribution to the final energy cost. It could be hypothesised that, with greater fins, more water would be displaced, but with less muscle activation, leading to a more economical swimming. Since neither SR, SL (Barbosa et al. 2008) and [LA] and PE changed, it is assumed that fins until 488 cm² of area, in maximal intensity, are not able to change energetic profile.

Conclusion
Areas of fins, relative to foot’s area, seem to be decisive for the spatio-temporal and physiological responses. This control may be essential for the correct prescription of using fins. Fins 488 cm² area can cause limited changes in spatio-temporal parameters. More studies should be conducted to elucidate issues related to biomechanics and physiology of swimming with the use of fins.

References


Acknowledgment
To CAPES, Brazilian Government, by the master scholarship.
Hydrodynamic quality factor as an objective quantitative characteristic of assessment of swimming technique

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Keywords: mathematical apparatus of the vibration theory, quality of the quasiperiodic process, a quantitative assessment of swimming technique from of the energy efficiency position, hydrodynamic quality factor

Introduction

Stroke efficiency is determined by its compliance with solvable tasks and high final result, level of athlete’s physical, tactical and psychological skills.

Stroke efficiency is estimated and controlled in real training and competitive exercises using the methodology estimating the travel speed of the common center of mass of athlete’s body (CCMAB) or the methodology of evaluation of the dynamics of closed cycle speed [1,2,5-7]. Closed cycle speed (CCS) of CCMAB travel is characterised by $V_{\text{max}}$, m/s – maximal values of swimming CCS in one cycle, $V_{\text{min}}$, m/s – minimal value of swimming CCS in one cycle and alternation of acceleration and inhibitory phases (Fig. 1).

![Figure 1](image)

**Figure 1** The dynamics of CCS of CCMAB in swimming, $V_{\text{max}}$, $V_{\text{min}}$, $V_{\text{mdl}}$, maximal, minimal and average values of speed of CCMAB respectively

CCS of CCMAB in swimming is known [2, 5-7] to change according to the quasiperiodic law, providing the opportunity to involve some conditions of mathematical apparatus of the vibration theory to estimate stroke efficiency in real movements [3].

The energy efficiency of the quasiperiodic process is estimated by the quality of the oscillating system $Q$. Quantitatively the quality $Q$ is equal to the ratio of energy saved in the system and the value of energy lost in one period of oscillations, multiplied by $2\pi$ [4].

The quality of the quasiperiodic process we study can be determined using the above mentioned definition of the quality of oscillating system as a ratio of energy saved in the system and energy used within one period of oscillations (without regard of the constant factor $2\pi$).

Since energy is definitely related to the squared travel velocity, in our case quality is equal to

$$K = \frac{V_{\text{max}}^2}{(V_{\text{max}}^2 - V_{\text{min}}^2)}$$

(1)

where: $V_{\text{max}}$, m/s—maximum CCS in one swimming cycle; $V_{\text{min}}$, m/s—minimum CCS in one swimming cycle.

We called the obtained characteristics ‘hydrodynamic quality coefficient’ (HQC) or hydrodynamic quality $Q$. 
It is known [2, 6] that stroke is more efficient when the difference between $V_{\text{max}}$ and $V_{\text{min}}$ is smaller. So, the less different $V_{\text{max}}$ and $V_{\text{min}}$ are, the higher HQC is, the less energy is required to maintain the high average speed of swimming, the more effective athlete’s stroke is.

The aim of research was the development and the approbation of the biomechanical characteristics for a quantitative assessment of swimming technique from of the energy efficiency position.

**Methods**

We used the method of hydroacoustic speed recording to estimate the dynamics of CCS of CCMAB [1,2]. This method measures CCS of CCMAB using the Doppler’s effect. The flow chart of methodology is adduced in Figure 2.

![Flow chart of the method of hydroacoustic speed recording](image)

Doppler effect is the changes of the frequency and length of the waves of the projector signal caused by movement of the projector and registered by the receiver. These changes are converted to the values of the projector’s moving speed. In our case this are the current values of the swimmer’s velocity.

**Results**

The obtained dynamics of CCS of CCMAB at crawl and butterfly was presented in Figures 3, 4.

![The dynamics of CCS of CCMAB at butterfly stroke](image)
Figure 4  The dynamics of CCS of CCMAB at crawl stroke

Table 1 contains the indices of HQC, calculated for different swimming styles for elite swimmers (men (n=8) and women (n=7)), measured at competitive speed.

According to the analysis of the findings, backstroke has the maximal energy efficiency out of all swimming styles, while breaststroke – minimal both among men and women. The average swimming speed for men using all styles was higher than among women. But women dominated in the energy efficiency of the technique compared to men, except for breaststroke.

Conclusions
1. The methodical approach to the quantitative assessment of the swimming technique effectiveness was proposed.
2. The biomechanical characteristic named ‘hydrodynamic quality factor’ was developed and tested in different swimming styles.
3. have suggested ‘hydrodynamic quality factor’ can be used to estimate the level of athletes’ technical skills in phased and current examinations and when developing model characteristics of the technique of performance of competitive and training exercises in sports swimming.

Table 1  HQC indices for different swimming styles for men (n=8)and women (n=7). (X—average value, σ—standard deviation)

<table>
<thead>
<tr>
<th>Swimming style</th>
<th>Vmax, m/s</th>
<th>Vmin, m/s</th>
<th>Vmidl, m/s</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Men</td>
<td>Women</td>
<td>Men</td>
<td>Women</td>
</tr>
<tr>
<td>Freestyle</td>
<td>1,88±0,06</td>
<td>1,63±0,09</td>
<td>1,56±0,06</td>
<td>1,37±0,10</td>
</tr>
<tr>
<td>Backstroke</td>
<td>1,68±0,10</td>
<td>1,59±0,08</td>
<td>1,40±0,11</td>
<td>1,35±0,09</td>
</tr>
<tr>
<td>Butterfly</td>
<td>2,01±0,11</td>
<td>1,66±0,14</td>
<td>1,09±0,11</td>
<td>0,94±0,09</td>
</tr>
<tr>
<td>Breaststroke</td>
<td>1,79±0,13</td>
<td>1,60±0,16</td>
<td>0,86±0,14</td>
<td>0,70±0,10</td>
</tr>
</tbody>
</table>
References

On the movement behaviour of elite swimmers during the entry phase

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Keywords: swimming, start, entry phase

Introduction

For years, allusions to the particular importance of the entry and underwater phase for the swim start have been a topic of interest in the swimming literature (Guimarães & Hay 1985; Bonnar 2001; Cossor & Mason 2001; Vilas-Boas et al. 2003). Based on Guimarães and Hay (1985) the movement phases during the swim start can be structured by the block-, flight-, and water-phase. Maglischo (2003) additionally subdivided the water-phase into the entry, gliding, and emersion-phase. Guimarães and Hay (1985) point out that 95% of the variance in the performance of the start can be explained by differences in the gliding phase (consisting of entry, gliding and emersion phase). In this regard, the gliding phase and the emersion phase have been investigated by several authors (Lyttle et al. 1999; Pereira et al. 2006; Elipot et al. 2009; Marinho et al. 2009; Elipot et al. 2010; Vantorre et al. 2010). In addition, there are various studies exhibiting that differences between starting techniques during the take-off phase do not necessarily result in different swim start times (McLean et al. 2000; Vilas-Boas et al. 2003; Welcher et al. 2008; Vint et al. 2009; Biel et al. 2010). In these studies, none of the variables representing the take-off on the block, the flight phase, or the gliding phase could account completely for the variance found in the swim start times. Based on these findings, the special importance of the entry phase was derived. Similarly, Sanders and Byatt-Smith (2001) and Sanders and Bonnar (2004) argue that, concerning the overall start performance, a greater emphasis should be given to the entry phase when compared to the take-off phase.

Remarkably, so far, no study has addressed the issue of the optimal movement behavior during the entry phase. However, speculations have been published on whether the pike or the flat dive would be more beneficial to the swim start performance (Maglischo 2003). For the entry phase, several variables have been investigated. These variables relate to the entry angle (Holthe & McLean 2001; Vilas-Boas et al. 2003; Miller et al. 2003; Gu, Tsai & Huang 2003; Kibele & Fischer 2009), the hip-angle at water entry (Kibele et al. 2007; Kibele & Fischer 2009), and the angle of attack (Gu et al. 2003). Studies that ascribe benefits to the flat dive (Counsilman et al. 1988; Kirner et al. 1989) contrast other studies showing advantages for a pike dive (Mills & Gehlsen 1996). Other studies did not find any differences between the two entry variants (Hobbie 1980; Holthe & McLean 2001; Gu et al. 2003; Fischer & Kibele 2009). Due to the different methodological approaches used to assess the entry
angle the studies published on the entry behavior cannot be properly compared (Guimarães & Hay 1985; Gu et al. 2003; Miller et al. 2003; Kibele et al. 2007; Fischer & Kibele 2009). In addition to differences between methodological approaches, kinematic parameters representing the entry behavior are difficult to assess as air particles are swept along the body surface distorting visibility in the video analysis. Until recently, this problem remained unresolved. However, using a new analysis tool ‘algorithm for the determination of body segment coordinates under blurred visual conditions’ the kinematic data of the movement behavior during entry can be analyzed (Kibele & Fischer 2009; Fischer 2013).

The objectives of this study were (a) to derive key parameters for the analysis of the entry phase and (b) to identify different movement strategies for the entry phase based on these parameters. We hypothesised that, in addition to the previously known strategies for the entry behavior (‘pike vs. flat’), further movement possibilities exist.

**Methods**

**Participants**

Twenty-eight male and 18 female swimmers participated in this study. All participants were members of the A- or B-category in the national team or the junior national team of Germany. Twenty-one swimmers preferred the grab start and 25 swimmers were using a track start technique.

**Procedure**

A cross-sectional study was conducted to assess the movement behavior during the entry phase of the swim start. Each participant performed a standardised 15 minute swim program to warm up. Then, the swimmers completed two starts using their preferred starting technique. The kinematic measurements were recorded during the swim start prior to a 25m sprint. The sprint tests were repeated three times with a 15-minute break between the tests. Only the trial with the best sprint result was used for the statistical data analysis to prevent for any specific emphasis on the swimmers’ side to be put on the swim start behavior. No feedback was given on the subjects throughout the measurements.

**Protocol**

A 2D strain gauge equipped OSB9 starting block was used to record the horizontal and vertical ground reaction forces (Kibele 2004). It was attached to the ground 6m distant from the lateral pool side. While the front edge of the starting block (surface area: 0.5x0.5m) was 0.65m above the ground level, the height in the back end was 0.70m. Three 50Hz DV cameras were used for the kinematic data acquisition. The time between the start signal and the head passage at 5m and 7.5m was used as a criterion for the starting performance. The block phase and the flight phase were recorded perpendicular to the movement plane with a Panasonic NV-GS120 EC camera. The entry phase was recorded with a Sony DCRTTV900E Pal camera located in an underwater box which was placed at the lateral pool wall 3 m distant from the block. The time at 7.5m was recorded with a third Sony VX-1000E camera. A shutter speed of 1/500s was used. Temporal synchronisation was achieved with a Genlock technique. For the calibration of the video images on the block, a 2x2m reference frame aligned with front edge of the block was digitised. For the underwater video analysis, another 2x2m reference frame was used at a distance of 3m from the starting block. All video images were digitised manually with the Simi-Motion system (version 8.0).

Aside from the middle of the ear, representing the head segment, the following segment end points were digitised: fingertip, wrist, elbow joint, shoulder joint, hip joint, knee joint, ankle, heel, and toe. The coordinates of the points were saved and subjected to a data filtering procedure (Butterworth 2nd order with 10Hz) prior to the calculation of the body center of mass using the de Leva method (1996). For the entry phase, the below water body coordinates were evaluated using the above mentioned algorithm for blurred visual conditions (Fischer 2013).
Kinematical analysis of the entry phase
Due to restricted visibility, the body segment locations could not be assessed through the segment end-points. Instead, the mid-lines of the segments were determined through a simple regression technique. For that purpose, three representative points on the presumed mid-line of a body segment were digitised. While the end-point we not visible for most segments, mid-lines could be properly identified. In this regard, the joint coordinates were calculated by the intersection of the mid-lines representing the adjacent segments. Given the particular importance of the trunk, this segment was treated with four representative points to determine a cubic spline function.

Statistical analyses
All data was accumulated as group mean values ± SD. Normal distribution was confirmed by the Kolmogorov-Smirnov-Test. However, due to space requirements, a descriptive data analysis is omitted. To identify the movement structure of the entry phase a factor analysis (PCA = principal component analysis with a rotating component matrix) was carried out. In this respect, the varimax method was used to maximise the variance of the factor loadings (Backhaus et al. 2005). Differences in the factor score coefficient matrix between gender and the starting techniques were analysed by student t-tests. To identify different strategies for the entry behavior, a cluster analysis using the Ward method with squared Euclidean distances as separating measures between the clusters was performed. Then, different cluster solutions were investigated on the basis of the provided factor analysis. The results of the cluster analysis were described by a dendrogram and a 2×3 analysis of variance (gender x cluster solution) to investigate the entry patterns. Post-hoc tests with Bonferroni-adjustments were conducted to identify significant differences. All analyses performed were conducted by the Statistical Package for Social Sciences (SPSS) version 22.0. The significance level was set at p < 0.05.

Results
Factor analysis for the identification of movement structures in the entry phase
In the factor analysis, seven factors explained overall 87.3% of the total variance. Thus, from the 24 different entry variables examined, only seven factors with eigenvalues greater than 1 were identify and implemented in a scree-plot (eigenvalue vs. component number). These factors represented the body posture at water-contact, the deflection behavior during the entry phase, the duration of the entry phase, the average horizontal velocity during the entry phase, the depth of the dive, the angular displacement in the hip-joint during the entry phase, and the effectiveness of the leg kick. The analysis demonstrates significant differences between the male and the female swimmers regarding the average horizontal velocity during the entry and the angular displacement of the hip-joint during the entry phase. In addition, highly significant differences between the genders were found for the duration of the entry phase. When comparing grab and track start, no statistical differences were detected.

Cluster analysis for the characterisation of the movement dynamics during the entry phase
The second part of this study was based on a cluster analysis to determine whether different profiles of the entry phase may exist. By using the cluster analysis, it was shown that three different movement patterns (flat dive, pike dive with a quick deflection, and pike dive with a delayed deflection movement) exist for the entry behavior. Highly significant differences between these movement patterns were found referring to the body position during water-contact and the angular displacement of the hip-joint during entry phase identified by a two-way ANOVA. In addition, a significant difference between the movement patterns was identified for the depth of the dive. Highly significant gender differences in the entry patterns were found in the factors: duration of and average horizontal velocity during the entry phase.
Discussion

It was the goal of the present study, to investigate the entry behaviour of female and male elite swimmers. In this regard, it is important to note that the entry angles measured were in line with other findings in the literature (Counsilman et al. 1988; Holthe & McLean 2001; Hay 1993; Miller 2003; Kazumasa et al. 2010). In addition, at first water contact, the inclination of the hip-hand interconnection relative to the water surface was found to be 38.7 ± 6.6° and the inclination of the CM-hand line 36.4 ± 5.4°. Kibele and Fischer (2009) have demonstrated that the hip angle at the moment of the CM entry is an important feature of the entry strategy. Therefore, a differentiated analysis of the angular displacement in the hip joint during entry phase was performed. Highly significant differences between the entry strategies were found in the hip angles at the water entry of the hands, the CM, and the feet. These differences were identified for both genders.

Further, in the ANOVA data analysis, a highly significant difference in the angle of attack was found between the entry patterns. In this regard, the post-hoc analysis showed a highly significant difference between the pike dive with a quick deflection movement and the other two entry strategies. In contrast, Gu et al. (2003) were unable to identify a significant difference in the angle of attack for their flat and the pike dives. The missing differences in the angle of attack in the study of Gu et al. (2003) could be explained by the small sample size of 13 swimmers. Alternatively, the lack of difference in the angle of attack could be related to the repeated measurement design as the angular displacement of the hip angle was not controlled by Gu and coworkers. Thus, for the pike dive with a quick deflection movement, swimmers may adopt a large angle of attack as well as a large entry hole to benefit from a large angular displacement in the hip joint during the water entry. In this regard, a hyperextended back may be utilised to prepare for a powerful dolphin kick.

Consistent with the findings of Gu et al. (2003), our results could not identify differences in the size of the entry hole (Pearson et al. 1998). However, these experimental findings in elite swimmers do not correspond with the general guidelines given by Maglischo (2003). Thus, elite swimmers possibly may not show large entry holes at all. For that level of expertise, the entry behaviour might have evolved to a point where larger entry holes are no more observed.

As a consequence of the different entry patterns, significant differences between swimmers showing these patterns were detected in the depth of the dive (flat dive: 0.80 ± 0.17m, pike dive with a quick deflection movement: 0.94m ± 0.18m; pike dive with a delayed deflection movement: 1.01m ± 0.27m). These results are in correspondence with the optimal depth of the dive of 0.90m reported by Elipot et al. (2010).

In conclusion, this study provides preliminary results for movement strategies in the entry phase of the swim start and can, thus, complement the existing studies on the movement strategies in the block, flight, and water phase. In this regard, three movement patterns were identified showing the most striking differences in the angular displacement of the hip-joint in the course of water immersion.

References


Development of a new resisted technique in active drag estimation

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Keywords: biomechanics, swimming, resistance, active drag, front crawl

This investigation aimed to develop a new technique for the estimation of active drag in front crawl swimming at the swimmer’s maximum swim speed, while allowing for intra stroke velocity fluctuation. This new resisted technique was developed using similar assumptions to that of the Velocity Perturbation Method (VPM) of Kolmogorov & Duplishcheva (1992). The investigation included twelve national and international male swimmers who were asked to perform two maximum effort free swim trials, two passive and two active drag trials. The data required for the calculation of active drag were maximum swim speed, which was derived from the free swim trials, and a force set between 4 to 10 N and which was dependent upon the mean value of passive drag. Mean active drag ranged from 68 to 123.2 N in front crawl. The mean active drag values found in this investigation were in agreement with those previously reported by Kolmogorov & Duplishcheva (1992) and Wang et al. (2007). These three techniques using resisted swimming (VPM, Wang et al. and the current study) provided similar values for mean active drag to one another.

Introduction

Drag force on the swimmer’s body through the water can be divided into active and passive drags. Active drag occurs when a swimmer propel themselves forward and passive drag when a swimmer glides in a streamline position (Kolmogorov and Duplishcheva 1992). The swimmer encounters passive drag only during the glide after start and turns; however, the majority of drag force which the swimmer encounters during swimming competition is active drag. Passive drag has been investigated by several researchers (Clarys 1979; Kolmogorov and Duplishcheva 1992; Shimonagata et al. 1998). A number of measurement techniques have been developed to assess and estimate active drag directly or indirectly, however, there has been controversy as the techniques used often reported varying values (Clarys and Jiskoot 1974; Clarys 1979; Formosa et al. 2011; Kolmogorov and Duplishcheva 1992; Kolmogorov et al. 1997; Mason et al. 2011; Toussaint et al. 2004; Wang et al. 2007; Zamparo et al. 2009).

Hollander et al. (1986) designed a measurement of active drag (MAD) system which is the only system that measures propelling forces directly. The MAD system measured active drag by measuring the propulsive force applied to paddles fixed to a force transducer in the pool whilst swimmers performed the front crawl action. Kolmogorov and Dupleishcheva (1992) estimated active drag using the Velocity Perturbation Method (VPM) at maximal swim velocity; once with a hydrodynamic body attached that produces an additional known resistance, and once without the added resistance. The measurement of active drag was based upon two assumptions; the swimmer was able to generate a constant mechanical power output in both conditions, and the swimmer maintained a constant average velocity during each trial.

Toussaint et al. (2004) assessed the difference between the active drag values measured with the MAD system (Hollander et al. 1986) and the active drag values estimated by the VPM technique (Kolmogorov and Dupleishcheva 1992). They reported that the main reason for the difference in active drag results was an unequal power output when swimming with and without added resistance during...
the VPM method. Wang et al. (2007) designed a new device to estimate active drag by using a gliding block to provide an adjustable drag which was attached to the swimmer by a force transducer. They calculated active drag based upon the equal power output assumption of Kolmogorov and Duplishcheva (1992) (with and without a small additional drag).

Mason et al. (2011) determined the value of active drag at maximal swim velocity by towing a swimmer at 5% higher than mean maximum velocity. The Assisted Towing Method (ATM) was designed to allow swimmers to have a fluctuating velocity which enabled them to maintain their normal stroke technique whilst being towed. The measurement of active drag was based upon the same assumptions as the VPM technique (equal power output in the free swimming and when being assisted with the tow).

The purpose of the present research was to implement a new technique to estimate active drag using an electrically braked resisted force rather than an assisted tow, whilst fluctuations in intra-stroke velocity were still allowed. This technique is similar to the methods of Kolmogorov & Duplishcheva (1992) and Wang et al. (2007), but enabled more precise control of the braking force and subsequent resisted swim velocity.

**Method**

Twelve national and international male swimmers (mean ± standard deviation: age= 20.5 years; height= 1.85 cm; weight= 79.5 kg, FINA point rank of over 750) participated in this research. Swimmers were required to complete all tests in one day starting with a 20 minutes warm-up. Swimmers performed at least one practice trial to become familiar with the nature of the experiment and were given 5 minutes rest between each trial to eliminate the influence of fatigue on their performance.

Firstly, each swimmer completed two maximum free swim velocity trials over a 25 m interval, starting from 35 m out, and the velocity measured over the interval 25 m to 5 m out from the wall using two 50 Hz cameras. Velocity was averaged from the two trials to determine the swimmer’s maximal free swim velocity. Secondly, two passive drag trials were completed at the swimmer’s free swim velocity. The passive drag trial was acceptable when the subject was able to maintain a streamline position just below the water surface and there was visible water flow passing over the head, back and feet (Formosa et al. 2010). Finally, the swimmers were then required to swim two trials with maximum effort with a belt attached around the swimmers’ waist and connected to a dynamometer mounted directly on a calibrated Kistler™ force platform (Kistler Instruments Type Z20916). Active drag trials were performed using an electrically braked cable to achieve a velocity 5% to 8% less than mean maximum swim velocity over a 25 m interval with velocity averaged over six full strokes. The force level was set between 4 to 10 N and adjusted if the resisted swim velocity was more than 8% less than free swim velocity.

The dynamometer and force platform were instrumented to capture the velocity and the force generated by the swimmer during each trial. Collecting the data was started by pressing a trigger signal at the beginning of six full strokes (beginning with right hand entry) and finished with another the trigger signal after the six full strokes were completed to allowed for digital data smooth. Data was sampled using a 12 bit analogue to digital board, with a sampling rate of 500 Hz. Prior to experimental testing, a range of cut- off frequency was examined to determine the most appropriate cut off frequency. Examining Active drag profiles demonstrated that an 8 Hz Butterworth low-pass digital filtered was most appropriate.

Active drag at the maximal mean swim velocity was computed using the difference between normal free swimming velocity and the measured resisted velocity, together with the force needed to slow the swimmer to the desired velocity range. The following equations were used to estimate active drag and were originally introduced by Kolmogorov and Duplishcheva (1992):
where \( F_{A1} \) is the active drag during free swimming, \( F_{A2} \) is the active drag resisted towing, \( \rho \) is water density, \( A \) is the front surface area of the swimmer, \( C_d \) is the drag coefficient, \( V_1 \) is the swimmer’s maximum mean swim velocity for free swimming, and \( V_2 \) is the decreased resisted velocity.

**Figure 2** Propulsive (\( F_P \)), Active drag (\( F_A \)) and Belt force (\( F_B \)) vectors in Resisted Method

As figure 2 shows the three forces vectors while a swimmer is resisted by the dynamometer,

\[
F_{P2} = F_{A2} + F_B
\]

where \( F_{P2} \) is the propulsive force during resisted swimming, \( F_{A2} \) is the active drag force resisted towing and \( F_B \) is the force needed to slow the swimmer to the desired velocity.

Based on the equal power assumption in both the free swimming and the resisted tow swimming conditions:

\[
P_1 = P_2
\]

where \( P_1 \) is the power output during free swimming and \( P_2 \) is the power output during resisted towing.

And therefore,

\[
F_{P1}, V_1 = F_{P2}, V_2
\]

At a constant swimming velocity, the mean propulsive force is equal in magnitude but opposite in direction to the mean active drag force (Toussaint et al. 1983). Therefore, substitution of \( F_{P2} \) and \( F_{P1} \), then gives:

\[
F_{A1}, V_1 = (F_{A2} + F_B), V_2
\]

Substitution of \( F_{A1} \) and \( F_{A2} \) then gives:

\[
\left( \frac{1}{2} C_d \rho A V_1^2 \right) V_1 = \left( \frac{1}{2} C_d \rho A V_2^2 \right) V_2 + F_B, V_2
\]

Rearranging the above formula to find \( C_d \):

\[
C_d = \frac{F_B, V_2}{\frac{1}{2} \rho A (V_2^3 - V_1^3)}
\]

Finally, substituting \( C_d \) in equation 1 and gives the active drag formula:

\[
F_{A1} = \frac{F_B, V_2}{V_2^2 (\frac{V_1^2}{V_2^2} - \frac{V_2^2}{V_2^2})}
\]
Data was collected using motion analysis software (Contemplas GmbH) and then processed using an export/import function in Contemplas linked to an AIS customised analysis program. The average from two active drag resisted trials and two passive drag trials of each subject was calculated. A Paired t-test was used to perform on the mean active drag and mean passive drag values. SPSS software (Windows version 19) was used for statistical analyses and a statistical significance set at the 95% confidence level (p<0.05).

**Result**

Fluctuating velocity resisted active drag parameters were computed for each of the swimmers. Mean value ± standard deviation (SD) of the active drag was calculated for each swimmer. Table 1 presents the active drag value of trials 1 and 2 and also, the mean value of active drag and passive drag for each swimmer at the maximal swim velocity.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Mean max velocity</th>
<th>Mean Passive drag</th>
<th>Active drag Trial1</th>
<th>Active drag Trial2</th>
<th>Mean Active drag ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.99</td>
<td>91.0</td>
<td>89.5</td>
<td>77.6</td>
<td>83.5 ± 8.4</td>
</tr>
<tr>
<td>2</td>
<td>1.83</td>
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<td>119.8</td>
<td>129</td>
<td>124.4 ± 6.5</td>
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<tr>
<td>3</td>
<td>1.74</td>
<td>104.5</td>
<td>76.0</td>
<td>88.1</td>
<td>82.1 ± 8.6</td>
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<tr>
<td>4</td>
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<td>75.5</td>
<td>109.0</td>
<td>92.7</td>
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</tr>
<tr>
<td>5</td>
<td>1.80</td>
<td>94.0</td>
<td>86.2</td>
<td>87.4</td>
<td>86.8 ± 0.8</td>
</tr>
<tr>
<td>6</td>
<td>1.91</td>
<td>109.7</td>
<td>101.3</td>
<td>90.6</td>
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</tr>
<tr>
<td>7</td>
<td>1.92</td>
<td>108.2</td>
<td>80.4</td>
<td>70.0</td>
<td>75.2 ± 7.4</td>
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<tr>
<td>8</td>
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<td>53.0</td>
<td>71.0</td>
<td>62.0 ± 12.7</td>
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<tr>
<td>9</td>
<td>1.82</td>
<td>76.2</td>
<td>107.4</td>
<td>101.1</td>
<td>104.3 ± 4.5</td>
</tr>
<tr>
<td>10</td>
<td>1.88</td>
<td>92.3</td>
<td>89.7</td>
<td>95.6</td>
<td>92.7 ± 4.2</td>
</tr>
<tr>
<td>11</td>
<td>1.80</td>
<td>96.0</td>
<td>86.8</td>
<td>99.8</td>
<td>93.3 ± 9.2</td>
</tr>
<tr>
<td>12</td>
<td>1.77</td>
<td>80.20</td>
<td>79.3</td>
<td>60.3</td>
<td>69.8 ± 13.4</td>
</tr>
</tbody>
</table>

| Mean        | 1.83              | 93.7             | 89.8              | 88.6              | 89.2 ± 16.7          |

The average of active drag and the average of passive drag were 89.2 ± 16.7 N and 93.7 N respectively. The paired t-test revealed statistically no significant differences between the active drag and the passive drag values (p=0.05).

**Discussion**

The primary aim of this research was to develop a new resisted technique in active drag estimation using an electrically braked resisted force. The result of this study indicated that there was no statistically significant difference between the active and passive drag measures. The small, non-significant, reduction in active drag compared to passive drag was similar to the result reported by Kolmogorov and Duplishcheva (1992), who did not perform any statistical test of the difference. Also another study found that no significant correlation (r=0.24) between the mean active drag value and the mean passive drag value (Shimonagata et al. 1998) and also, they reported that the mean active drag (64.85 ± 16.53 N) was 76% of the mean passive drag (85.24 ± 21.36 N).

The results of the present research are in conflict with prior findings reported by Formosa et al. (2011) and Mason et al. (2010). In those studies, the mean active drag values were considerably higher than the passive drag values (for example, Formosa et al. 2011: active drag 262.4 ± 33.4 N and passive drag 80.3 ± 4.0 N). While a higher maximal swim velocity produces more active drag, the difference in average velocity between the two studies is not enough to explain the difference in calculated drag. It can be explained that active drag may not change proportionally to velocity squared, and therefore an
increase in towing velocity rather than a decrease in resisted velocity could possibility affect calculated drag. The difference between active drag calculated by assisted and resisted techniques could alternately be explained by the swimmers’ ability to produce constant power under all conditions. If power was increased during resisted swimming and decreased during assisted swimming (or vice versa) then, that could be an alternate reason for the difference between the assisted and resisted techniques.

The mean active drag results of this research were similar to those previously reported by Kolmogorov & Duplishcheva (1992) and Wang et al. (2007). For example, Kolmogorov & Duplishcheva (1992) reported that the active drag value of a male was 104 N at a maximum velocity of 1.80 m/s and also, Wang et al. (2007) reported that the active drag value of a male was 105 ± 5.63 N at a maximum velocity of 1.83 m/s. In the present study, the mean active drag value of subject 9 was 104.3 ± 4.5 at a mean maximum velocity of 1.82 m/s. In contrast, the active drag values found in the ATM technique at constant velocity (Formosa et al. 2011; Sacilotto et al. 2012) and the ATM technique with fluctuating velocity (Mason et al. 2011; Hazrati et al. 2013) were significantly higher than those for the studies using resistive forces. The reason for these differences in active drag values is likely to be a consequence of using an assisted tow method, rather than a resisted method. While, the active drag values obtained from the ATM technique with the fluctuating velocity were much lower than those obtained from the constant velocity technique (for example, Hazrati et al. 2013: the mean active drag of male swimmers 140.2 ± 19.8 N at 1.87 m/s and Formosa et al. 2011: the mean active drag 262.4 ± 33.4 N at 1.92 m/s), they were still higher than all the studies that used resisted tow techniques. The present study, which used the same equipment as the four ATM studies, produced similar results to the previous two resisted techniques reported by Kolmogorov & Duplishcheva (1992) and Wang et al. (2007). It therefore seems likely that the higher drag values of the ATM technique (Formosa et al. 2011; Mason et al. 2011; Sacilotto et al. 2012; Hazrati et al. 2013) are caused by differences between assisted and resisted tow techniques, rather than a result of the methods used to control the amount of tether force.

Conclusion

The three resisted techniques (Kolmogorov & Duplishcheva (1992), Wang et al. (2007) and the current research) which estimated active drag during free swimming through the use of known resistive forces provided similar values to each other. In contrast, drag values calculated using the velocity-assisted techniques Mason et al. (2011), Formosa et al. (2011) Sacilotto et al. (2012) and Hazrati et al. (2013) provided substantially larger values. Further research should be undertaken to determine why this relationship exists between the resisted and assisted testing conditions.

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Drag reduction by underwater undulatory swimming? An experimental and numerical approach

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Keywords: undulatory swimming, drag reduction, drag coefficient, CFD, PIV

Introduction

From fish locomotion we learned that low drag values can be achieved during active propulsion. Thereby a carefully adjusted traveling body wave pumps the fluid caudally. Similar to an active flapping plate (Taneda & Tomonari 1974) the usage of a sophisticated body movement reduces and partly prevents the flow separation along the body (e.g., Anderson et al. 2001). The fish use the tail fin to control the generated vortices (Anderson et al. 1998).

Despite of the anatomical limitations of the human body (non-smooth and segmented body with limited flexibility) swimmers try to copy successful strategies such as undulatory swimming from fish locomotion. Moreover, it is still unclear whether and, if yes, to what extend the human swimmers are able to reduce drag values during the underwater phases after start and turn. One possibility to investigate this question is to compare passive drag (during gliding) and active drag (during active propulsion).

Passive drag can be determined by measuring deceleration or by measuring the force by pulling a subject. Due to the intertwining of drag and propulsion in swimming there is no satisfactory method for a direct experimental determination of active drag. Only for front crawl swimming it is possible to judge active drag by the MAD-system (Measure Active Drag; Hollander et al. 1986). However, this method is not suitable for undulatory swimming. This requires the usage of more complex tools such as Particle Image Velocimetry (PIV) (e.g., Matsuuchi et al. 2009; Hochstein & Blickhan 2011) and
Computational Fluid Dynamics (CFD, e.g. von Loebbecke et al. 2009; Cohen et al. 2012; Hochstein et al. 2012). The latter provides forces on the moving swimmer during a kick cycle (e.g., von Loebbecke et al. 2009). Net forces on the undulating swimmer have been elegantly calculated using smoothed particle hydrodynamics (Cohen et al. 2012). There was no attempt to calculate the drag coefficient during undulatory swimming and the previous CFD studies are not validated.

The main goal of this paper is to calculate the drag coefficient during gliding and during active undulatory swimming using numerical flow simulations of a scanned female swimmer and to check whether the swimmer is able to swim with drag coefficients comparable to those for gliding.

The presented work only considers the local experimental flow fields with the aim to validate the numerical calculations. The used numerical simulations are the first which were partly validated by the qualitative comparison with the experimental flow field of the same swimmer with identical kinematics. With the local vortices, it is possible to estimate the amount and the loss of the transferred momentum.

**Material and methods**

**Experimental setup**

A female national level swimmer (personal best 200 m butterfly: 2:12.9) swam in an indoor pool (size: 20 m x 8 m x 0.5-2 m; water temperature: 28-30 °C) with undulatory motion in a prone position (arms extended at the front) at her preferred frequency. After undulatory acceleration the swimmer swam with maximum speed through the camera recording window. To prevent effects of wave drag generation the swimmer was requested to swim within a depth of 0.8-1 m (e.g., Vennell et al. 2006; Vorontsov & Rumyantsev 2000).

To visualise the generated flow of the central sagittal plain during undulatory swimming and during gliding the method of a two-dimensional Particle Image Velocimetry (PIV) was used (Hochstein & Blickhan 2011). Thereby the water was seeded with unexpanded polyamide particles (Degussa, Vestosint 1121, diameter 100 μm), which had nearly a neutral density in comparison to water. The path of levitating particles—illuminated by a green laser light sheet—was monitored at 250 Hz with a high speed camera (Phantom V12, Vision Research, Wayne, USA). Local flow velocities were calculated using a cross correlation algorithm to obtain a flow field including a qualitative and quantitative characterisation of vortex generation and separation (DynamicStudio 3.14, Dantec Dynamics, Skovlunde, Denmark).

Simultaneously, the swimmer’s motion was captured using a video camera (Basler A602fc; 30 Hz) and LED marker on anatomical landmarks (wrist, shoulder, hip, knee, ankle, and toe). The motion of the marker points was tracked using WinAnalyze 2.1.1. (Mikromak, Berlin, Germany) and post processed in MATLAB 2009b (The MathWorks Inc., Natick, USA). For more details of the experimental setup (PIV and kinematics) see Hochstein & Blickhan (2011) and Hochstein et al. (2012).

The drag coefficient \( c_D \) for gliding (passive drag coefficient) is calculated by the deceleration of the swimmer induced by drag.

\[
\dot{m}(t) = -0.5 c_D \rho_W A \cdot \dot{x}(t)^2. \tag{1}
\]

Thereby is \( m \) the swimmer’s mass, \( x(t) \) is the horizontal displacement of swimmer’s hip marker (represents approximately swimmer’s center of mass), \( c_D \) is the drag coefficient, \( \rho_W \) is the density of water, \( A \) is the swimmer’s frontal area and \( t \) is the time. Solving equation (1) for the swimmer’s horizontal velocity and integrating according to the time yields
\[
x(t) = \frac{1}{v_{x0}} + \frac{c_D \rho_w A}{2m} \cdot t
\]

\[
x(t) = \frac{2m}{c_D \rho_w A} \cdot \ln \left(1 + \frac{c_D \rho_w A}{2m} v_{x0} \cdot t\right).
\]

The drag coefficient \(c_D\) as well as the initial horizontal velocity \(v_{x0}\) can be calculated by the regression (e.g., MATLAB curve fitting toolbox) of the experimental measured horizontal motion of the hip marker \(x(t)\) (Eqn. 3).

**Numerical setup**

The swimmer’s silhouette was scanned by a 3D body scanner (VITUS Smart XXL 3D, Human Solutions, Kaiserslautern, Germany) and subsequent her measured joint kinematics were implemented to obtain a preferably naturally moving 3D swimmer model. The general flow pattern around the moving swimmer and the forces generated by the swimmer were calculated with Computational Fluid Dynamics (CFD) using OpenFOAM as well as moving and deforming meshes. For more details of the numerical setup see Hochstein et al. (2012).

The resultant net force acting on the swimmer’s body for a constant swimming velocity is the sum of the propulsion and the drag force and can be calculated (without the negligible viscous wall friction) by

\[
F_{\text{Res}} = F_{\text{Prop}} + F_{\text{Drag}} \equiv \int_{A_p} p n \, dA_S.
\]

Thereby \(p\) is the pressure acting on the swimmer’s body, \(n\) is the normal vector of the body surface and \(A_S\) is the swimmer’s total body surface area. The propulsion can be estimated by the axial momentum added into the wake by the balance across two planes \(A_p\) (the first plane \(A_1\) is 1.1 m in front of the swimmer and the second plane \(A_2\) is 0.1 m behind the swimmer) normal to the swimming direction \(v_\infty\) (Schade & Kunz 1989):

\[
F_{\text{Prop}} \approx \int_{A_1} \rho_w v (v \cdot n) \, dA_p + \int_{A_2} p n \, dA_p.
\]

with \(v\) is the local flow velocity vector. With equation (4) the drag is the horizontal net force subtracted by the horizontal propulsion and with equation (1) the drag coefficient is

\[
c_D = \frac{F_{\text{Res}} - F_{\text{Prop}}}{\frac{\rho_w A}{2m} v_{x0}^2}.
\]

**Results**

**Measured and calculated flow field**

Whereas the numerical calculations capture the whole 3D-flow field in the vicinity of the swimmer, our PIV-analyses are restricted to 2D-sections. Within these sections major features could be reproduced. Swimmers produce vortex rings after the up and down kick (confirmed by the numerical 3D flow field) which merge to longitudinal vortex strings in swimmer’s wake (see Hochstein et al. 2012). The longitudinal vortex strings do not appear in our sagittal observations. Here observations in the transversal plane (Fig. 2) are necessary.
The flow field of the sagittal 2D-PIV experiments show more vortex generation during active propulsion compared to passive gliding mainly in the leg region (see Hochstein & Blickhan 2011).

This increased vortex generation indicates increased drag. Larger oscillation of the hand and arm regions can result in disadvantageous vortex generation in the head region, which does not contribute to propulsion (Fig. 1). By contrast, a smaller oscillation in the cranial body parts helps both to avoid producing vortices and to prepare the flow for the undulatory pump (flow preformation).

With respect to drag it was shown exemplarily that an advantageous technique can minimise vortex separations (Fig. 1) which may result in a reduced drag coefficient.

**Drag coefficient**

For gliding the drag coefficient of the female national level swimmer is similar for both the estimation based on numerical CFD-simulations ($c_D = 0.3$; Eqn. 6) and that derived from experimental data ($c_D = 0.25 – 0.29$; Eqn. 3) using in both cases identical kinematics (Tab. 1).

For undulatory swimming first results of the simulated (CFD) drag coefficient show about ten times higher drag values ($c_D = 2.98$; mean value during a kick cycle) during active propulsion compared to passive gliding ($c_D = 0.3$).

**Table 1** Overview of the drag coefficient $c_D$ during gliding and during undulatory swimming based on numerical simulations (CFD; Eqn. 6) and experimental analysis (Eqn. 3).

<table>
<thead>
<tr>
<th>Situation</th>
<th>Calculation type</th>
<th>Drag coefficient $c_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gliding</td>
<td>CFD</td>
<td>0.3</td>
</tr>
<tr>
<td>Gliding</td>
<td>Experimental</td>
<td>0.25 – 0.29</td>
</tr>
<tr>
<td>Undulatory swimming</td>
<td>CFD</td>
<td>2.98</td>
</tr>
<tr>
<td>Undulatory swimming</td>
<td>Experimental</td>
<td>Cannot be determined</td>
</tr>
</tbody>
</table>

**Figure 1** Exemplary comparison of the flow generated by the swimmer for two swimmers of different performance levels

a) The less skilled swimmer uses large amplitudes of the hands and the arms and has a head position resulting in vortices already below the head region (red and blue open circle) and generating a downward jet (gray arrow). b) Swimming with smaller amplitudes in the arm region (the skilled swimmer) avoids this jet and allows the generation of the undulatory pump (blue open circle; Hochstein 2013).
Discussion and conclusions
Measured and calculated flow field

The present work uses the comparison between the numerical CFD simulations and the experimental PIV results with respect to the flow field to show similarities which can be considered as an initial step for the validation of the numerical simulations (CFD). For a more detailed explanation of the flow field behind and around a human swimmer see Hochstein & Blickhan (2011), Hochstein et al. (2012) and Hochstein (2013).

The results of the numerical simulations explain the absence of a stable flow pattern in the wake of the swimmer in our PIV-measurements. In these measurements we monitored only the selected central sagittal observation slice. The numerical results indicate that the resulting vortex rings after the up and down kick (similar to von Loebbecke et al. 2009; Cohen et al. 2012) merge into longitudinal vortex strings in swimmer’s wake (Fig. 2; Hochstein et al. 2012). To identify these vortex structures it is necessary to monitor the flow in slices parallel to the swimmer’s central sagittal plain.
Drag coefficient

For passive gliding the simulated drag coefficient \( (c_D = 0.3) \) match the experimental observed values \( (c_D = 0.25-0.29; \) Tab. 1). Drag values, presented here, are in agreement to the experimental results of Vennel et al. (2006) with drag values in the range of 0.25-0.28 and are in a similar order of magnitude but lower than the values of Marinho et al. (2009; CFD; drag values about 0.48 depending on the swimming speed) and Costa et al. (2011; CFD about 0.4 and experimental data about 0.5).

As to the intertwining of drag and propulsion in undulatory swimming there is actually no satisfactory method for a direct experimental determination of active drag while swimming which do not interfere with the swimmer. The towing of buoys with known drag (VPM; velocity perturbation method; Kolmogorov & Duplishcheva 1992) offers an alternative for the measurement of passive drag as well as active drag. However, this method is characterised by a number of assumptions (e.g., Toussaint et al. 2004) and can only be used in a restricted manner.

Thus, only numerical simulations can be used for calculating the local forces of swimmer’s body acting on the water masses. However, the calculations of the propulsion as well as the resulting active drag and drag coefficient are defective and have to be considered as rough estimations. Additionally, the human swimmer can be considered as a system with distributed propulsion (in agreement to the results of von Loebbecke et al. 2009). Parts of the generated propulsion (local propulsion) can be used to compensate the local drag in particular cranial body parts.

Historically, the drag force and drag coefficient are defined for fixed rigid bodies such as airfoils. In most cases, the stationary flow induces drag depending quadratically on speed (Newton friction). However, the flow around a permanently moving swimmer is highly unsteady (e.g., von Loebbecke et al. 2009; Cohen et al. 2012, Hochstein et al. 2012) and the concepts of stationary situations may not be applicable. The drag coefficient estimated represents the mean value over a complete kick cycle. It varies during the kick with phases in which either thrust or drag dominates (e.g., von Loebbecke et al. 2009). In a distributed propulsive system the drag determined may vanish (Hochstein 2013). The large drag value estimated points towards large losses which only to a minor extend have been compensated by the swimmer. In future, it is necessary to develop new concepts which are specifically formulated for the case of a self-propelling swimmer with an unsteady flow field.

The ten times higher active drag values as compared to the gliding drag rather deny a significant reduction of active drag (Tab. 1). However, we cannot exclude this as small variations in technique may lead to drastic variations in drag. In addition, the techniques for low drag may be far from the undulatory technique used in training and competition focusing on thrust generation. We conclude that swimmers are able to reduce their drag values only little.

Besides of movement shape certainly affects drag. Nevertheless, first results of numerical simulations of a five segmented swimmer-like plate model can be interpreted as an indication that the effect of the swimmer’s motion on drag by far exceeds the effect of a facsimile body shape of the swimmer (Reinhardt 2013). Robot models with simplified geometries may be useful to complement the numerical studies lined out above.

Acknowledgments

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References

Sculling and unroll-body-action techniques in the thrust movement of synchronised swimming based on three-dimensional motion analysis

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Abstract

The thrust movements both under and above water of nine top-level synchronised swimmers were analysed using 3D DLT method. Peak height, height of shoulder, elbow and wrist, unroll time, sculling time, maximum vertical velocity of the body’s centre of gravity, wrist velocity, hip and shoulder angle are analysed as kinematic parameters. Since the peak height index (peak height/body height) and the maximum vertical velocity of the body’s centre of gravity were related significantly, it is necessary to increase the vertical velocity of the body’s centre of gravity in order to increase the peak height. Swimmers with a high peak height index demonstrated a shorter unroll time with a quick extension of the hips. Furthermore, in sculling, the arm’s position was maintained near the surface of the water.
during the arms pull phase. The arm’s position was closer to the water surface with a higher vertical velocity of the wrists during the arms turn. It was found that important techniques to improve peak height in thrust movement, are to unroll with a shorter time, and to not lower the arms at the beginning of thrust movement and to turn arms rapidly and catch the water closer to the surface with horizontal forearms.

**Keywords:** synchronised swimming, thrust movement, unrolling, sculling

**Introduction**

In synchronised swimming, the thrust movement is the technique that achieves the greatest height (Homma & Ito 2005). The thrust movement is an instantaneous technique in which swimmers boost up with their feet from the water’s surface; it is an important basic movement in the required elements of the technical routines. According to FINA rules, thrust is defined as a movement ‘from a submerged back pike position, with the legs perpendicular to the surface, a vertical upward movement of the legs and hips is rapidly executed as the body unrolls to assume a vertical position. Maximum height is desirable.’ In thrust movement, maximum height can be reached by using techniques of unroll-body-action and sculling.

In addition, scores for all movements were set which are based upon the relative difficulty of each essential synchro specific elements within a given transition (FINA 2014). An assessed score of thrust movement of 37.0, is categorised into the highest value transitions with maximum dynamic height. Since synchronised swimming is a three-dimensional action enacted using both the space above and below the water’s surface, kinematic analysis has still mostly not been undertaken. There are no past instances of research having simultaneously analysed both underwater and above water movements in synchronised swimming. The purpose of this study was to clarify the technical factors for increasing peak height in the thrust movement through the use of three-dimensional motion analysis both under and above water.

**Methods**

**Participants**

Nine female synchronised swimmers (age: 19.9 ± 3.06 years, height: 1.61 ± 0.04 m, weight: 52.5 ± 3.51 kg) participated in the study as volunteers. Four of them were Olympic swimmers and the other 5 were all top-level swimmers. All the participants agreed to the informed consent statement.

**Experiment device and set-up**

A total of 4 cameras, 2 on land and 2 in the water, were synchronised, and thrust movements were filmed. Both land and water cameras were set up so that their fields of vision would intersect at right angles. The filming range was as follows: x-axis: 3 m, y-axis: 3 m, z-axis: 2 m above water and 2.5 m underwater. The filming was 60 frames per second, with a shutter speed of 1/100 s. The device used for calibration consisted of a wooden frame with a wire bearing the calibration mark slung through it, on top of a flat cube of styrofoam material designed to make the frame float on water. This device was put on the water’s surface and moved to nine different locations in the filming range by pulling on the wire attached to the lower part of both sides of the pool.

**Data collection**

Tape marks were attached to all the participants’ acromion points, elbow joint centres, carpal joint centres, middle finger bases, knee joint centres, ankle joint centres, and thumb ball points in order to achieve accurate digitisation. From the images taken by each of the four cameras, the coordinates of the calibration points and those of 24 points on each of the participant bodies were analysed using a motion analysis system (DKH, Frame-DIAS II). The 3-dimensional coordinates were computed using the 3D DLT method. With respect to the bodies of the participants who performed the thrust movement, the x-axis was the front-back direction, the y-axis was the left-right direction, and the z-
axis was the vertical direction. The 3-dimensional coordinates that were obtained were smoothed to the most appropriate 6-Hz cutoff frequency by using a low-pass filter.

**Definition of unroll and sculling phases in thrust movement**

Unroll is the movement whereby, from a submerged back pike position, the pelvic region is rounded and the upper body makes flat into a vertical position. In this study, ‘unroll’ is defined as the period between the moment when the hips begin to extend (the beginning of the unroll), until the moment when it is in a vertical position (the end of the unroll). In this study, sculling was divided into 3 phases: ‘Arm Pull’—from the beginning of the thrust movement (the moment when the toes leave the water) until the beginning of the arm turn, ‘Arm Turn’—from the moment in which the horizontal extention begins until the moment in which both hands face towards the front of the body, and ‘Arm Push’—from the end of the arm turn until the reaching of the highest point.

**Data analysis**

The kinematic parameters in the study were as follows (Figure 1): Peak Height—the peak height reached at the toe’s z-coordinate, peak height index (PHI)—peak height/body height, shoulder, elbow and wrist heights, unroll time, arm turn time, wrist velocity, vertical velocity of the body’s centre of gravity (CGV) and hip angle. In order to examine the variables related to height, Pearson’s rank correlation coefficient was used in the statistical processing.

\[
\begin{align*}
\text{Water} & \quad \text{Surface} \\
\text{Submerged back pike position} & \quad \text{Vertical position} \\
\text{Phases of thrust movement} & \\
\text{Arm Turn Start} & \quad \text{Arm Turn End} & \quad \text{Peak Height} \\
\text{Arm Turn Total time} & \quad \text{Unroll Total time} & \quad \text{Total time}
\end{align*}
\]

Figure 1. Kinematic parameters in this study and unroll and sculling phases in the thrust movement.

**Results**

In this study, a PHI value was used as an evaluation index for high thrust movements. Average peak height for nine swimmers was 1.19 ± 0.05 m and average PHI was 0.74 ± 0.02. Swimmer A had the highest PHI, 0.76, and swimmers H and I had the lowest PHI, 0.71. There was a significant positive correlation \((r = 0.642, p < 0.05)\) between the peak height index (PHI) and the maximum vertical velocity of the body’s centre of gravity (max CGV). Figure 2 shows the body’s centre of gravity for swimmer A, who had a high PHI, as well as for swimmer I, who had a low PHI. From the beginning to the end of the arm turn, a spike in the vertical velocity of the body’s centre of gravity (CGV) was
observed. Vertical velocity displayed a sharp increase for swimmer A with a high PHI. Max CGV was 1.79 m/s for swimmer A and 1.22 m/s for swimmer I.

The variable characteristics of kinematics in relation to unroll-body-action

A significant negative correlation ($r = -0.74, p < 0.05$) was observed between the relative value (%time) of the total unroll time and the PHI. Total unroll time was 45.9% time for swimmer A and 68.9% time for swimmer I.

Figure 3 shows the hip angle and CGV from the start of the thrust movement until the max CGV. Swimmer A, who had a high PHI value, showed a significant increase in CGV at 0.35 s, and reached 1.8 m/s in CGV at 0.55 s. A sharp increase with respect to hip angle was observed at around 0.40 s. In contrast, in swimmer I, who had low PHI values, although two increases in the CGV were observed, they were more gradual in comparison to the swimmers with high PHI values, and reached 1.2 m/s in CGV.

Figure 3. Relationship between hip angle and CGV. Swimmer a with a high PHI started hips extension at approximately 0.4 s, and after that, increased sharply the hips angle to 126 deg. Swimmer i with a low PHI started hips extension at 0.35 s and gradually increased and reached the hip angle (90 deg).
The variable characteristics of kinematics in relation to sculling

There was a significant positive correlation ($r = 0.63$, $p < 0.05$) between the maximum wrist vertical velocity and the PHI. When the swimmer with a high PHI was compared to the swimmer with a low PHI, the arm turn total time was observed to be shorter, and vertical velocity was larger.

Figure 4 shows the height of the shoulder, elbow and wrist in relation to the height of the water’s surface during thrust movement for swimmer A with a high PHI, and swimmers I with a low PHI. At arm turn start point, swimmer A showed same heights of wrist and shoulder (-0.36 m), and swimmer I showed difference of 0.11 m between wrist height (-0.44 m) and shoulder height (-0.33 m). Wrist and elbow heights at arm turn end point were -0.15 m, -0.29 m in swimmer A and -0.19 m, -0.42 m, respectively. Swimmer A showed higher wrist height and smaller difference between wrist and elbow heights.

Discussion

A significant positive correlation was found between the PHI and the max CGV. In addition, since a clear difference was observed in the changes to the CGV between swimmers who had a high PHI and swimmers who had a low PHI, improvement in the max CGV was considered to be one of the most important factors. It is understood that it is necessary to raise the max CGV in order to increase the peak height, and sculling and unrolling are considered the primary techniques in bringing about such a change.

The unroll-body -action factor in relation to peak height

In this study, there is a significant negative correlation between the PHI and the total unroll time; specifically, it was observed that, as the total unroll time decreased, the PHI showed a tendency to increase. In addition, the hip angle change and the change in the CGV during thrust movement show that when a large increase occurs in the change in the CGV, an even more significant ascension point can be observed. Based on the sudden increase in the degree of the hip angle observed before this increase, unrolling is considered to be effective during the second ascension point. It was found that higher CGV is needed to improve height. Therefore, unroll must be executed sharply and quickly.
The sculling factor in relation to peak height

Sculling is also suggested to have an effect on the max CGV because of an observable clear increase in the CGV from the beginning to the end of the arm turn. A significant positive correlation was observed between the PHI and the maximum vertical velocity of the wrist during the arm turn, just before the max CGV was achieved. In addition, judging from the significant increase in the velocity in the wrist that occurs in all swimmers just before the max CGV is achieved, it can be said that the maximum vertical velocity of the wrist with quick arm turn technique has an effect on the max CGV.

When comparing swimmers who had a high PHI with those who had a low PHI a difference was observed in the change to the wrists and elbows. A high PHI swimmer sculled closer to the water’s surface during the arm turn. In addition, a high PHI swimmer had smaller differences between wrist and elbow heights at the arm turn end. It is concluded that keeping the position of wrist closer to the water surface during arm turn, and sculling the forearm horizontally and closer to the water surface at the arm turn end are important techniques to increase height. This agreed with Homma’s suggestion (2006) that keeping forearms horizontal is important to the techniques for support scull.

Conclusions

We examined the technical factors for increasing peak height in the thrust movement. The thrust movements both under and above water of nine top-level synchronised swimmers were analysed using 3D DLT method. In conclusion, it is necessary to increase the vertical velocity of the body’s centre of gravity in order to increase the peak height. The important techniques of unroll-body-action and sculling to improve peak height in thrust movement are: unrolling must be executed sharply with a quick extension of the hips, not be lowering the arms at the beginning of thrust movement, turning the arms rapidly and catching the water closer to the surface with horizontal forearms.

References


Difference of hydrodynamic force on foot between front crawl six-beat and flutter kicking

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Keywords: six-beat kick, flutter kick, delta pressure, hydrodynamic force, front crawl swimming

The purpose of this study was to investigate the hydrodynamic difference between six-beat kick in front crawl swimming and flutter kick without rolling of the whole body. The subject was a male college swimmer. Two pairs of small pressure sensors were attached on the dorsal and plantar sides of both of the swimmer’s feet during trials, which involved flutter kick while holding a kickboard and six-beat crawl swimming. The motion of the swimmer’s right leg and arm was recorded using an underwater video camera during the trials. In the six-beat trials, the positive and negative peak values of the difference of pressure between dorsal and plantar sides were not similar in the three downbeats and upbeats during one stroke cycle. It was suggested that there were hydrodynamic differences between flutter kick and six-beat kick in front crawl swimming.
Introduction

The six-beat kick, which is the most popular rhythm of the arms and legs in front crawl swimming, includes three leg beats per one arm stroke (Maglischo 2003). The three kicking motions were proposed to differ kinematically because they are affected by the rolling motion of the whole body. Maglischo (2003) explained such differences among the three kicking motions in six-beat front crawl swimming in detail. Sanders and Psycharakis (2009) described the kinematic characteristics of the six-beat kick in sinusoidal rhythms represented as Fourier harmonics. However, their report did not describe the hydrodynamic characteristics of six-beat front crawl swimming. Namashima (2006) simulated the dynamics of the whole body in six-beat front crawl swimming using a swimming human simulation model: SWUM. However, no reports described the differences among the three kicks in six-beat crawl swimming. Many swimmers train their kicking motion in flutter kick without whole-body rolling. It is thus considered important to understand the hydrodynamic characteristics of six-beat kicking with whole-body rolling and the differences from flutter kicking without rolling.

The purpose of this study is thus to investigate the hydrodynamic differences between six-beat kicking in front crawl swimming and flutter kicking without rolling of the whole body.

Method

A well-trained male college freestyle swimmer, whose height, weight, age, career and personal best of 100-m freestyle were 1.67 m, 60.0 kg, 22.1 yrs, 14.1 yrs and 53.5 sec, respectively, participated in the experiment. Trials were performed under two conditions: 1) 25-m kicking while holding a kickboard by upper limbs and 2) 25-m front crawl swimming with six-beat kicking. The subject performed the trials three times with different levels of subjective intensity.

Pressure on the swimmer’s feet was measured during each trial. Small pressure sensors, 6 mm in diameter and 0.7 mm thick (PS-05KC, Kyowa Inc., Japan), were attached on the swimmer’s third metacarpophalangeal joint (MP joint) on the dorsal and plantar sides of both feet (Fig. 1). Pressure signals were recorded using a data-logger (LP-WS10SP-PL01, Logical Product Inc., Japan), which included a signal amplifier and an A/D converter sampling at 200 Hz. Delta pressure $\Delta P$ was calculated as follows:

$$\Delta P = P_{dorsal} - P_{plantar}$$

(Eq. 1)

where $P_{dorsal}$ and $P_{plantar}$ are the pressure measured on the dorsal and plantar sides of each foot, respectively. In this research, $\Delta P$ was used as an index to evaluate hydrodynamic force exerted on the swimmer’s foot.

![Figure 1](image_url) Positions of attachment of pressure sensors on swimmer’s foot (left) and a pressure sensor (right)

The motion of the swimmer’s upper and lower right limbs was recorded over a distance of 10 to 15 m in each trial using an underwater camera (DMX-WH1E, Sanyo Electric Inc., Japan). The positions of the
fingertips of the right hand, tips of the toes of right foot, ankle, knee and hip joints on the sagittal plane were calculated by a two-dimensional direct linear transformation method, and smoothed using a digital low-pass IIR filter with a cut-off frequency of 3 Hz. The mean swimming velocity was calculated from the horizontal displacement of the right hip joint over 10 to 15 m in each trial. The vertical displacements of the toe tips, ankle, knee and hip joints were analyzed using $\Delta P$ on the swimmer’s foot. In the six-beat swimming trials, the position of the right hand’s fingertips was calculated to identify the timing of arm stroke phases.

Pressure measurement and motion recording were synchronised by a synchronising signal generator (LP-WSY11, Logical Product Inc.) and an LED synchroniser (PTS-110, DKH Inc., Japan) (Fig. 2).

![Figure 2](image)

Figure 2 Experimental set-up to measure pressure on the feet and record swimming motion in flutter kick and six-beat front crawl swimming

**Results**

The mean swimming velocities were 1.03, 1.10 and 1.14 m/s in flutter kick trials while holding a kickboard, and 1.47, 1.59 and 1.72 m/s in six-beat front crawl swimming trials. Figures 3 and 4 show the $\Delta P$ of each foot over 10 to 15 m in the flutter kick and six-beat trials, respectively. It was observed that $\Delta P$ was positive, which meant that there was greater pressure on the dorsal side than on the plantar side, during downbeat, while there were negative values during upbeat. In addition, the absolute peak value during downbeat was greater than during upbeat in both kicking and six-beat trials.

In the kicking trial, $\Delta P$ showed a similar pattern corresponding to the down/upbeat of the legs (Fig. 3). In the six-beat trial, the positive and negative peak values of $\Delta P$ were not similar in the three downbeats and upbeats during one stroke cycle (Fig. 4). The three downbeats of the right leg during one arm stroke cycle occurred during gliding, downsweep and recovery phases of the right arm (Fig. 5). The largest peak in the right leg downbeat was observed during the downsweep phase of the right arm, shortly after the right side hip joint reached its deepest point (Fig. 5).
Figure 3  Pressure differences between dorsal and plantar sides on swimmer’s feet in flutter kick trial

The vertical solid and dashed lines show the timings of start of right leg downbeat and upbeat, respectively.

Figure 4  Pressure differences between dorsal and plantar sides on swimmer’s feet in six-beat front crawl trial

The vertical solid and dashed lines show the timings of start of right leg downbeat and upbeat, respectively.
Timings of entry and release of the right hand are indicated as ‘Ent’ and ‘Rel’ with arrows in the bottom left panel. The vertical solid and dashed lines in the left panels show the timings of the start of downbeat and upbeat, respectively.

Figure 5  Delta pressure on right foot (top left), vertical displacements of right foot’s toe tips and hip joint (bottom left) and right hand’s path on the sagittal plane corresponding to the duration indicated by the gray rectangle in the bottom left panel (right) in a six-beat trial

Discussion

It would be intuitive for the pressure on the dorsal side of a swimmer’s foot to be greater than that on the plantar side during downbeat, and vice versa during upbeat. This was observed under both trials of flutter kick and six-beat front crawl swimming (Fig. 3 and 4). In addition, a larger absolute $\Delta P$ was observed during downbeat than during upbeat in both trials, which shows that the downbeat would contribute to producing a larger hydrodynamic force to propel the body forward. Maglischo (2003) mentioned that the downward kick was largely responsible for the propulsive force. This would be an important technique for kicking commonly observed in flutter and six-beat kicking. Determination of the direction of the hydrodynamic force on the feet was needed in order to evaluate propulsive force. However, this direction was not measured in our research. The motion of the legs also contained lateral components (Maglischo 2003), so it was necessary for the attitude and velocity of a swimmer’s feet to be represented in three dimensions to estimate the propulsive force on the feet. In the future, the combination of pressure measurement and three-dimensional motion analysis should provide more insight on the propulsion produced by kicking in swimming.

Different positive and negative peaks of $\Delta P$ during three down/upbeats were observed in the six-beat trials (Fig. 3), while there were similar repeating patterns in the flutter kick trials (Fig. 4). These findings showed that there are hydrodynamic differences between flutter kick and six-beat kick in front crawl swimming. In the six-beat trials, the largest positive peak in right leg downbeats appeared during the downsweep phase of the right arm, shortly after the right hip joint reached its deepest point with rolling of the whole body (Fig. 5). The body rolling would make the hydrodynamic force on the foot greater during the arm downsweep phase than during the other two downbeat phases because the rolling motion moves the hip downward and accelerates the leg downward (Fig. 6). On the other hand, the vertical hip motion with body rolling and the different patterns of $\Delta P$ were not observed in the flutter kick trials. It was suggested that a particular technique of kicking with body rolling would be applied in front crawl swimming. However, it would be difficult to apply this technique in flutter kick while holding a kickboard because there is little body rolling. It is hoped that the technique of kicking with rolling of the whole body will be taken into account in training and coaching of the kicking technique in front crawl swimming.
The contribution of the kick in front crawl swimming has been reported and discussed by various researchers. Hollander et al. (1987) reported that the mean powers of 18 elite swimmers were 122.7 W and 14.6 W by arm and leg, respectively, from measurements of active drag. Nakashima (2006) simulated the dynamics of the whole body in six-beat front crawl swimming and explained that thrust due to a kick did not appear since tangential drag force became larger with an increase in swimming speed due to a hand stroke, although the kick itself was intended to produce thrust. In our research, the larger hydrodynamic force observed in the arm downsweep could contribute to produce a larger propulsive force effectively. As indicated earlier, determination of the direction of the force would be needed to discuss the propulsion. Yanai and Wilson (2008) mentioned that the flutter kick generates moments that counterbalance the leg-sinking effect of buoyancy in order to maintain horizontal alignment. The downsweep motion of the arm produces an upward force and more leg-sinking moment, so the larger hydrodynamic force on the foot would contribute to maintenance of the horizontal alignment and decrease drag force, which decelerates the swimming velocity of the body. As the downbeat of the leg during arm downsweep, the three kicking motions during one stroke cycle might make different contributions to propulsion in front crawl swimming.

**Conclusions**

There are suggested to be hydrodynamic differences between kicking without whole-body rolling and six-beat kicking with the rolling in front crawl swimming. The whole-body rolling would affect kicking motion and produce different hydrodynamic forces on the swimmer’s feet in six-beat front crawl swimming.

**References**


Optimising individual stance position in the swim start on the OSB11

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Keywords: swim start, OSB11 starting block

Abstract
The aim of this study was to evaluate systematic variations of the preferred stance of elite swimmers in relation to their swim start performance on the OSB11. Variations of the preferred stance were examined regarding the front leg (left vs. right), the centre of mass height (low vs. high), the stance width (narrow vs. wide), and a rear vs. a front weighted stance. Two thirds of the subjects displayed either improvements or no changes in swim start performances through stance variations of their preferred stance configuration. For half of the subjects, at least one stance alternative provided a better swim start time than the preferred stance. The average improvements in the swim start performance were found to be 0,06s with extreme values as large as 0,14s. The majority of the swim start improvements were associated with a front weighted stance, a decreased foot distance and an elevated centre of mass position. For this stance configuration, shorter block times were observed. In this regard, it is assumed that short block times are essential for the swim start performance on the OSB11.

Introduction
Since 2010, the OSB11 starting block model has been used for national and international championships. It provides clear advantages in swim start performance as compared to the previously used OSB9 device (e.g. Honda et al. 2010; Biel et al. 2010). However, there is scarce knowledge on the optimal stance position for swimmers with respect to their individual body length or leg preference (e.g., Slawson et al. 2011; Takeda et al. 2012). For example, Slawson et al. (2011) conducted a study on 32 British elite swimmers analyzing the effects of the stance width (feet placed in tandem position and feet placed shoulder wide in parallel position), the foot rest positions, and the preferred front leg. One of the most striking results in this study was that the optimal stance position on the new OSB11 was different for males and females. For example, these authors showed for the male swimmers that a wide stance width was associated with increases in block time and attenuated horizontal and vertical take-off forces in conjunction with a decreased horizontal take-off velocity. Thus, a narrow stance with a tandem foot position is beneficial for male swimmers. However, for the female swimmers, a wide stance position was associated with increased horizontal take-off forces and decreased absolute and relative flight distances. In a separate, single case study, Slawson and coworkers confirmed that the side preference for the front leg, the stance width, and the wedge position are the most important variables for the stance position on the block.

The study of Slawson et al. identified some important general trends with regards to the gender-specific effect of varying the width of stance on starting performance, as well as wedge position and preference for the front leg. However, general trends are likely insufficient to identify the optimal foot positioning for each individual separately. Aside from gender and leg preference, leg strength and body weight must be considered as well since peak forces during the block phase have been identified as major predictors of swim start performance (Kibele et al. 2005; Slawson et al. 2013; Beretic et al. 2013; Fischer 2013). In addition, according to the study of Welcher et al. (2008), the weighting of the legs during the stance must be considered. These authors showed that the rear-weighted track start had a better combination of time and velocity than the front-weighted track start. Finally, the centre of mass (CM) height must be accounted for as this measure as it has been shown to determine block time which in turn is major prerequisite for swim start performance (Hay & Guimaraes 1983; Fischer 2013). In conclusion, according to the individual anthropometry and the swimmer’s strength abilities, the start block set-up and stance cannot be evaluated by simple univariate analyses.
For a first approach to this problem, a systematic variation of the preferred stance position in the track start of elite swimmers on the OSB11 was used to evaluate their swim start performance (time between the starting signal and the head-passage at 5m). In this regard, variations of the individually preferred stance were examined regarding the front leg (left vs. right), the CM height (low vs. high), the stance width (narrow vs. wide), and a weighted stance (rear vs. front) estimated by the horizontal distance of the hip joint to the front edge of the block. The magnitude of the variations was expressed relative to the individual leg length. Kinematic and kinetic measures were analyzed to evaluate the swim start performance.

**Method**

**Subjects:** Fourteen male and five female elite swimmers (females: 24.8 ±2.7y age; 1.74 ±0.02m height, 63.8 ±5.09kg body mass; males: 23 ±1.5y age; 1.88 ±0.06m height, 83.6 ±10.7kg body mass) participated in the study. Fifteen subjects preferred freestyle while one male and one female preferred butterfly and one male and one female preferred breaststroke.

**Instrumentation:** For the kinematic data analysis, 2 video cameras (Sony DCR-TRV900E Pal operated at 50Hz) were placed vertically at a height of 1.35 m above the water level and horizontally in parallel to the front edge of the block, and at 5m after the block. While the first camera was used to analyze the take-off behaviour on the block, the second camera was utilised to capture the time between the starting signal and the head passage at 5m. A 2D-strain gauge equipped starting block (Kibele 2005) with an OSB11 surface measured the horizontal and vertical ground reaction forces.

**Procedures:** Systematic variations of the preferred stance position accounting for the CM heights and distances relative to the front edge of the block, as well as the stance width, were related to the standard deviations (SD) found in a preceding pilot study (Experiment 1 in Kibele, Biel & Fischer 2013) with six male and seven female elite swimmers (females: 22.1 ±4.0y age; 1.78 ±0.06m height, 65.2 ±5.4kg body mass; males: 23.8 ±2.3y age; 1.90 ±0.03m height, 85.8 ±5.4kg body mass). In this experiment, the individually preferred stance configurations in elite swimmers were analyzed. The means and SDs were expressed relative to the individual leg lengths of the male and female swimmers separately. For example, the CM height, relative to the individual leg lengths, was 0.72 ±0.04 for the females and 0.73 ±0.04 for the male swimmers. Furthermore, relative step lengths, expressing the horizontal distances between the toes of both feet, of 0.66 ±0.07 were found for the females and 0.63 ±0.08 for the males. For the present study, the SDs were reconverted relative to the gender and the leg length of each subject. These SDs were then added and subtracted respectively to the preferred stance configurations (Fig. 1 left side). For example, a low CM height for a subject was determined by his CM height in the preferred stance position minus one SD reconverted to the subject’s leg length. Thus, in addition to the preferred stance, 8 configurations were possible for each leg: CM height (low vs. high) x CM distance (rear vs. front weighted stance), and stance width (narrow vs. wide). However, because of motor coordination demands, for each leg, only four of the eight possible configurations could be eventually maintained on the block. These configurations are as follows:

- narrow stance with CM position high-front (No. 1)
- wide stance with CM position high-back (No. 2)
- wide stance with CM position low-front (No. 3)
- wide stance with CM position low-back (No. 4).

Therefore, aside from the preferred stance, a total of eight swim start variations were analyzed. Three trials were used for each configuration. Prior to the swim start variations, the subjects performed their preferred stance conditions. Subsequently, the variations of the stance configuration were analyzed in random order and across three non-consecutive days.
For simplicity reasons, the hip-joint landmark was used as an estimate of the CM location. For the stance width of a male subject, for example, the SD 0,66 from the pilot study was multiplied with the given leg length of a subject and the result was added to the preferred stance width (wide) or subtracted (narrow). Then, the closest wedge position was used for the swim start trial. A video display was used to control the required stance configurations. Here, an overlay reference grid (Fig. 1 right side) was used to indicate the various hip joint positions.

Figure 1 left side: stance parameters: CM-length (rear weighted vs. front weighted start), CM-height (high vs. low), and step length (narrow vs. wide), right side: video display to control for the required CM location.

**Parameters:** For each subject, the mean values across valid trials were evaluated for the following kinematic take-off parameters: block time, horizontal take-off velocity (mean velocity across the first three images in the flight phase), take-off angle (inclination of CM trajectory during the first 3 images in the flight phase), flight distance (between front end of the block and the point of hip entry) relative to the body height, entry angle (inclination of the CM-hand interconnection), and hip angle at entry (angle between shoulder, hip, and knee joint at hand entry). For take-off dynamics, the vertical and horizontal peak forces were evaluated across the valid trials.

**Statistics:** A two-way repeated measures analysis of variance (ANOVA) was calculated to identify main effects and interaction effects for the selection of the front leg and for the four stance configurations. Post-Hoc tests were calculated with Bonferroni corrections for the Tukey-test. To assess reliability, Cronbach’s α was calculated for all parameters measured.

**Results**

Across all stance configurations, the deviations for the hip joint landmark from the target position were -0,049 ±0,039m in the vertical direction and -0,040m ±0,053m in the horizontal direction. Accordingly, the mean deviations for the CM coordinates from the target position were -0,041 ±0,036m in the vertical direction and -0,027m ±0,051m in the horizontal direction. To prevent overlapping in CM locations in the different stance configurations, trials were excluded from the statistical data analysis if their CM deviation from the target was larger than the smallest difference between the various target CM locations. Subsequently, 12% of all the trials were excluded.

For the remaining trials, 13 of the 19 subjects showed swim start improvements for the stance alternatives better than or equal to the preferred stance position. However, for 6 swimmers, any alteration of their preferred stance configuration caused a deteriorated swim start time. For half of the subjects, at least one stance alternative provided a better swim start time than the preferred stance. The mean improvements were found as large as 0,06s. The largest increase in the swim start
time was 0.14s. Table 1 lists the number of cases where swim start performance improved due to changes in stance configuration. Although a systematic tendency for an optimal stance configuration was not detected, a narrow stance with a high CM position (No.1) showed the most improvements to the preferred stance condition (see Table 1).

Table 1: Number of subjects and their stance configurations with a swim start performance better than for the preferred stance posture (multiple counts included)

<table>
<thead>
<tr>
<th>stance configuration with CM position and step length</th>
<th>high-front narrow (No.1)</th>
<th>high/back wide (No.2)</th>
<th>low-front wide (No.3)</th>
<th>low-back wide (No.4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>preferred leg in front position</td>
<td>8</td>
<td>2</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>non-preferred leg in front position</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

Aside from the hip angle at entry ($r_{IC} = 0.60$), strong reliability values were found for the block time ($r_{IC} = 0.93$), the horizontal take-off velocity ($r_{IC} = 0.68$), the take-off angle ($r_{IC} = 0.86$), the flight distance relative to the body height ($r_{IC} = 0.94$), and the entry angle ($r_{IC} = 0.84$). For take-off dynamics, Cronbach’s $\alpha$ values for the vertical peak force ($r_{IC} = 0.97$) and the horizontal peak force ($r_{IC} = 0.99$) were assessed.

For ANOVA data analysis, a significant main effect for the leg factor leg was identified in the block time ($F = 7.7; p < 0.05$; -2.8% difference between the legs), the swim start time at 5m ($F = 12.1; p < 0.01$; -3%), the horizontal take-off velocity ($F = 28.5; p < 0.01$; +4.2%), and the vertical peak force ($F = 11.6; p < 0.01$; +4.8%). For these parameters, superior results were found for the preferred leg. For the hip angle at first water contact, a significant main effect was identified as well ($F = 9.7; p < 0.05$) demonstrating mean values for the preferred leg of 163° ±10.6° and for the non-preferred leg of 158° ±11.4°.

Table 2: Mean values and standard deviations for the kinematic and dynamic parameters with significant main effect for the stance configurations

<table>
<thead>
<tr>
<th>stance configuration with CM position and step length</th>
<th>high-front narrow (No.1)</th>
<th>high/back wide (No.2)</th>
<th>low-front wide (No.3)</th>
<th>low-back wide (No.4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>block time (s)</td>
<td>0.77 ±0.04 2,4</td>
<td>0.85 ±0.05 1,3,4</td>
<td>0.76 ±0.04 1,4</td>
<td>0.88 ±0.05 1,2,3</td>
</tr>
<tr>
<td>swim start time (s)</td>
<td>1.61 ±0.14 4</td>
<td>1.67 ±0.11</td>
<td>1.59 ±0.10 1,4</td>
<td>1.70 ±0.13 1,3</td>
</tr>
<tr>
<td>entry angle (°)</td>
<td>39.6 ±1.9</td>
<td>40.1 ±2.2 4</td>
<td>39.8 ±2.6</td>
<td>38.5 ±1.5 2</td>
</tr>
<tr>
<td>flight distance relative to body height</td>
<td>1.56 ±0.1</td>
<td>1.58 ±0.08 3</td>
<td>1.54 ±0.09 2</td>
<td>1.57 ±0.09</td>
</tr>
<tr>
<td>horizontal take-off velocity (m/s)</td>
<td>4.34 ±0.35</td>
<td>4.42 ±0.34</td>
<td>4.30 ±0.31 3</td>
<td>4.40 ±0.32 4</td>
</tr>
<tr>
<td>horizontal peak force (N/kg) in BW</td>
<td>1.24 ±0.22 2,4</td>
<td>1.05 ±0.16 1,3</td>
<td>1.21 ±0.23 2,4</td>
<td>1.01 ±0.15 1,3</td>
</tr>
</tbody>
</table>

Note: Significant differences in the post-hoc analysis are indicated by superscripted stance configuration numbers.

Significant main effects for the four stance configurations were found for the block time ($F = 31.0; p < 0.01$), the swim start time ($F = 12.1; p < 0.01$), the entry angle ($F = 3.8; p < 0.05$), the relative flight distance ($F= 4.4; p < 0.05$), the horizontal take-off velocity ($F = 3.7; p < 0.05$), and the vertical peak force ($F = 29.7; p < 0.01$). The main effect for the swim start time, however, is solely based on the differences in the block times. For the post-hoc analysis, the mean values and SDs with significant differences are listed in Table 2. A significant statistical interaction between the factors front leg and stance configuration was found for the horizontal take-off velocity only.

**Discussion**

In this study, two thirds of the subjects displayed either improvements or no changes in swim start performances based on stance variations in comparison to their preferred stance configuration. The average improvements in the swim start performance were found to be 0.06s with extreme values as large as 0.14s. While these values appear insignificant, a number of Olympic races were won within milliseconds. For example, during the Olympic freestyle races for women in Beijing 2008, Britta
Steffen (Germany) won the 100m race by 4 ms to Lisbeth Trickett (Australia). For the 50m freestyle race, Britta Steffen won by as little as 1ms to Dara Torres from the USA. Therefore, even it seems worthwhile to analyse the optimal stance configuration for the individual swimmer.

Aside from issues related to the spatial precision of the stance configurations, a major objection to the present study was that the swimmers’ preferred stance configuration might have been optimal from the beginning. This possibility could have been true for the 30% of subjects decreasing their swim start time through a change in their stance configuration. In this case, this approach would aid in improving swim start times.

In the past, for the traditional OSB9 starting block, an inverse relationship between block time and horizontal take-off velocity was found independent of the starting technique used. In this regard, larger take-off velocities were observed in line with longer block times (e.g., Blanksby et al. 2002; Miller et al. 2003; Vilas-Boas et al. 2003). Therefore, for each swimmer’s anthropometry and strength abilities an optimal relationship between block time and horizontal take-off velocity was needed. As the increased length in the new OSB11 starting block offers a better opportunity for the acceleration of the CM, this problem is raised once again.

The results from the present study show that for the majority of the swim start improvements were associated with a narrow stance with an elevated CM. For this stance configuration, shorter block times were observed. Therefore, on the new OSB11, the impact of reducing block time on the swim start performance might be increased. In contrast, on the OSB9 starting block, Welcher and colleagues (2008) showed the rear-weighted track start to be superior to the front-weighted track start. For the rear-weighted track start, longer block times in line with longer acceleration pathways were observed. The same argument is supported by Fischer (2013). In his PhD thesis, a structural equitation model was used to analyze the swim start predictors on the OSB9 block. According to Fisher’s analysis, to improve swim start performance, longer block times may be tolerated to increase the horizontal take-off velocity. This strategy might be reversed for the new OSB11. Here, the slanted footrest provides enhanced conditions for the horizontal force development within a short amount of time. Therefore, keeping the block time short may pay off. According to Tab. 2, short block times and large horizontal peak forces were found for the front-weighted stance positions (No.1 and No.3). For these two stance configurations, due slightly higher horizontal peak forces, a narrow step length with an elevated CM position (No. 1) could prove to be more beneficial than a wide step length with a low CM position (No.3). In fact, preceding studies showed that wide step lengths were associated with a deferred force development in both legs (Fischer 2013).

**Conclusion**

The study shows that, for a random sample of elite swimmers, preferred stance could be improved substantially through a variation of the stance parameters. A general trend for an optimal stance position was not detected. However, from the number of improvements observed in the different stance alternatives, it appears that a high CM position with a narrow stance width and a front-weighted start provides substantial opportunities for swim start improvements.

**Literature**


Differences in stroke technique of skilled swimmers to exert hand propulsion between the front crawl stroke and the butterfly

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Keywords: drag, lift, dynamic pressure

Introduction

The arm movement of the front crawl stroke consists of an entry, a downsweep, an insweep, an upsweep, a release and a recovery while the arm movement of the butterfly consists of an entry, an outsweep, an insweep, an upsweep, a release and a recovery (Maglischo 1993). Both swimming strokes of the front crawl stroke and the butterfly have the insweep and the upsweep phases, which are the main the propulsive phases for both swimming strokes. The front crawl stroke is the fastest stroke among the four competitive strokes, and the butterfly is the second fastest stroke. The butterfly may be considered as the symmetrical stroke of the front crawl stroke in terms of the two stroke phases. Thus, a good front crawl stroke swimmer seems to be a good butterfly swimmer. However, the stroke technique to exert hand propulsion in the front crawl stroke is different from the one for the butterfly because the butterfly involves the movement of trunk undulation.

The dynamic pressure approach has been developed to quantify hand propulsion exerted by a swimmer, and the hand propulsive technique of skilled sprint-crawl swimmers was re-evaluated (Kudo & Lee 2010; Kudo, Miwa & Sakurai 2013). The dynamic pressure approach also provides
of the hand propulsive drag and lift. By quantifying hand propulsion due to drag and lift forces, hand displacement, velocity and acceleration, we can analyse the detail of hand propulsive technique. The aim of this study was, therefore, to investigate if the hand propulsive technique of the front crawl stroke was different from the one for the butterfly using the dynamic pressure approach.

**Method**

Three skilled swimmers as shown in Table 1 participated in this study after they signed informed consent. They were asked to swim the front crawl stroke and the butterfly at their race pace in a swimming pool where the motion capture system (Qualisys, Sweden) was set up above and under water. Three reflective markers were attached on the right hand (the third finger tip, triquetral and scaphoid) to determine hand kinematics, and two reflective markers were attached on the right and left ASIS to determine a swimming speed. Twelve pressure sensors with a portable data logger (MMT, Japan) were attached on the swimmer’s hand to quantify the magnitude of hydrodynamic forces exerted by the swimmers (Kudo & Lee 2010). The portable data logger, synchronised with the motion capture system, was attached on the back of the swimmer. A right-handed Cartesian coordinate system was set as the x-axis defined the direction of swimming, the y-axis defined the side-to-side direction, and the z-axis defined the vertical direction. All data were recorded at 100 Hz while the swimmer swam from 12.5 to 20 m of the swimming pool.

**Table 1**  Three swimmers participated in the present study

<table>
<thead>
<tr>
<th></th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>Specialised Stroke</th>
<th>Specialised Distance</th>
<th>Qualified Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swimmer A</td>
<td>1.84</td>
<td>80</td>
<td>Fr / Ba</td>
<td>Short</td>
<td>Olympic</td>
</tr>
<tr>
<td>Swimmer B</td>
<td>1.84</td>
<td>81</td>
<td>Fr / Ba</td>
<td>Long</td>
<td>Olympic</td>
</tr>
<tr>
<td>Swimmer C</td>
<td>1.76</td>
<td>67</td>
<td>IM</td>
<td>Long</td>
<td>Universiade</td>
</tr>
</tbody>
</table>

The reflective marker and pressure data were smoothed using a low-pass Butterworth filter. Using the three markers on the hand, the local reference hand-centric system was defined. Hydrodynamic forces acting on the hand (R) for one stroke in the front crawl stroke and the butterfly in the local reference system were determined by the dynamic pressure approach (Kudo et al. 2008; Kudo & Lee 2010). The sum of the x-component of the predicted hydrodynamic forces acting on the hand in the local reference system was computed as hand propulsion (P). Knowing the hand velocity and the predicted hydrodynamic forces on the hand, drag force acting on the hand was quantified. The x-component of drag force on the hand was propulsive drag force exerted by the hand (PD). The difference between P and PD was hand propulsive lift (PL). The swimming speed for the one stroke was calculated by using the x-coordinates of the midpoint between the two ASIS markers. The one stroke used for the quantification of the hand propulsion was decomposed into three phases; downsweep (front crawl stroke) or outsweep (butterfly), insweep and upsweep. For the present study, the insweep was from the frame when the hand started moving backwards to the frame before the hand started moving outwards, and the upsweep was the frame that the hand started moving outwards to the exit of the hand out of the water. The mean of R, P, PD and PL among the three swimmers was computed for the insweep and upsweep phases. The ratio of the hand propulsive drag to the hand propulsive lift (PD/PL) was computed. Also the mean magnitude of hand velocity in the x-direction (|Vx|) and in the yz-plane (|Vyz|) and the mean angle of attack (α) among the three swimmers were computed for the two stroke phases.

**Results**

Table 2 shows the mean values of R, P, PD and PL in the insweep and upsweep phases. The difference between R and P was greater in the upsweep phase than for the insweep phase of both strokes (insweep: 12% and upsweep 44% relative to P). Mean P and PL in the insweep of the butterfly (56 and 24 N) were greater than for the front crawl stroke (46 and 15 N) while mean PD in the insweep of
both swimming strokes was similar. Mean P, PD, and PL in the upsweep of the butterfly were similar to the ones for the front crawl stroke. In the insweep phase, PD exerted by the swimmers during the front crawl stroke was two times greater than PL while PD/PL was approximately 1 for the butterfly. In the insweep phase $|Vx|$ of the front crawl stroke was greater than for the butterfly while $|Vx|$ in the upsweep of the front crawl stroke and $|Vyz|$ in both phases of the butterfly were greater than for the front crawl stroke (Table 3). AP in both phases of the front crawl stroke was greater than for the butterfly (Table 3). Figure 1 shows P, PD and PL during the front crawl stroke and the butterfly of Swimmers A and B. The greatest P was seen in the upsweep phase of the butterfly of Swimmer B. The hand propulsion during swimming consisted of the hand propulsive drag and lift, and the hand propulsive drag was inversely proportional to the hand propulsive lift for both swimmers and strokes.

Table 2  Propulsion, propulsive drag and lift exerted by the hand in the front crawl stroke and the butterfly

<table>
<thead>
<tr>
<th></th>
<th>Front crawl stroke</th>
<th>Butterfly</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>P</td>
<td>PD/PL</td>
</tr>
<tr>
<td>Insweep</td>
<td>53 (14)</td>
<td>46 (9)</td>
</tr>
<tr>
<td>Upsweep</td>
<td>57 (23)</td>
<td>39 (16)</td>
</tr>
</tbody>
</table>

Values are mean (standard deviation). R: resultant force exerted by the hand (N), P: propulsion exerted by the hand (N), PD: propulsive drag exerted by the hand (N), PL: propulsive lift exerted by the hand (N).

Table 3  Hand velocities and angle of attack in the front crawl stroke and the butterfly

<table>
<thead>
<tr>
<th></th>
<th>Front crawl stroke</th>
<th>Butterfly</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>Vx</td>
<td>$</td>
</tr>
<tr>
<td>Insweep</td>
<td>1.41 (0.18)</td>
<td>1.46 (0.16)</td>
</tr>
<tr>
<td>Upsweep</td>
<td>1.24 (0.23)</td>
<td>2.16 (0.23)</td>
</tr>
</tbody>
</table>

Values are mean (standard deviation). $|Vx|$ : magnitude of hand velocity in the x-axis (m/s), $|Vyz|$ : magnitude of hand velocity in the yz-plane (m/s), $\alpha$: angle of attack (°).
Figure 1   Propulsion (P), propulsive drag (PD), and propulsive lift (PL) exerted by the hand of Swimmers A and B during the front crawl stroke and the butterfly; top-left: front crawl stroke of Swimmer A, top-right: butterfly of Swimmer A, bottom-left: front crawl stroke of Swimmer B, bottom-right: butterfly of Swimmer B.

Discussion
The present study investigated the hand propulsive technique of skilled swimmers in the front crawl stroke and the butterfly by quantifying the hand propulsion (P) resulting from the propulsive drag (PD) and lift (PL). The swimmers who participated in the present study have been competing in the international races of the front crawl stroke and the butterfly but were different in terms of their specialised distances. The present study found some similarities and differences in the hand propulsive technique between the front crawl stroke and the butterfly of the swimmers. Active drag estimated by MAD-system for swimmers whose profiles were similar to Swimmer A in the present study was about 85 N at the swimming speed of 1.83 m/s (Toussaint et al. 2004). Swimmer A exerted hand propulsion of 56 and 51 N in the insweep and upsweep phases, respectively. At the constant swimming speed, Swimmer A would exert approximately 63% of propulsion by the hand while the rest might be exerted by the other limbs such as the forearm and legs.

For both strokes, P in the insweep phase was greater than P in the upsweep phase by 7 and 17 N in the front crawl stroke and the butterfly, respectively. However, R of the front crawl stroke in the insweep phase was smaller than R in the upsweep phase by 4 N, and the difference in R of the butterfly between the insweep and the upsweep phases was 6 N, which was smaller than the difference in P. The results indicate that the swimmers utilised the total force exerted by the hand in the insweep phase more efficiently than in the upsweep phase as the hand propulsion. This may be the point where the swimmers in the present study should improve their technique. However, it might be that the swimmers needed to exert the non-propulsive force more in the upsweep phase for a different reason from propelling body forward. They might exert non-propulsive force in the upsweep phase to maintain the horizontal alignment of the body. The downbeat of the second kick in...
the butterfly starts during the upsweep phase (Maglischo 1993) and could generate leg-raising torque with buoyant torque so that non-propulsive forces exerted by the hands in the upsweep phase might play a role in generating leg-sinking torque against the leg-raising torque to remain the body horizontal alignment (Yanai 2001).

In the insweep phase, $P$ in the butterfly was greater than $P$ in the front crawl stroke while in the upsweep phase $P$ of the butterfly was similar to $P$ of the front crawl stroke. The different $P$ in the insweep phase was because $PL$ in the butterfly was greater than for the front crawl stroke. Thus, the $PD/PL$ of the butterfly was approximately 1 whereas the $PD/PL$ of the front crawl stroke was about 2. The $|Vyz|$ and $\alpha$ results are consistent with the finding of different $P$ in the insweep phase of both strokes because $PL$ increased as $|Vyz|$ increased and $\alpha$ in the butterfly became an angle to maximise lift on the hand (Schleihauf 1979). This increase in $PL$ in the insweep phase of the butterfly could be also due to the movement of trunk undulation. The hand would move upward during insweep phase of the butterfly due to the trunk undulation, which causes the increase in $|Vz|$ resulting in the greater $PL$.

In the insweep phase $PD$ in the butterfly was similar to $PD$ in the front crawl stroke while a different $|Vx|$ was observed and could have resulted in the different drag force of approximately 8 N (hand area = 0.017 from the three swimmers and $C_d = 1.2$ at $\alpha = 60^\circ$ and $C_d = 1.0$ at $\alpha = 45^\circ$ (Schleihauf 1979)). The expected difference in $PD$ due to the different $|Vx|$ was not observed possibly because of the different hand acceleration (24.6 m/s$^2$ for the front crawl stroke and 28.9 m/s$^2$ for the butterfly). Hand acceleration induced an additional hydrodynamic forces on the hand (Kudo, Wilson & Ross 2013; Rouboa et al. 2006). Flow around the hand becomes unsteady when the hand accelerates, and the effect of the flow unsteadiness on hydrodynamic forces acting on the hand such as vortices and added mass resulted in the increase of hydrodynamic forces on the hand (Dabnichki 2011; Takagi et al. 2013).

The greatest variance of $PD/PL$ among the three swimmers was seen in the upsweep phase of the front crawl stroke as $PD/PL$ of swimmers A, B, and C was 2.4, 0.7, and 1.1, respectively. The different $PD/PL$ between swimmers A and B can be due to the different specialised distance. Swimmer A as the short distance swimmer exerted more propulsive drag (36 N) than swimmer B as the long distance swimmer (19 N) in the upsweep phase of the front crawl stroke. On the other hand, swimmer B exerted more propulsive lift (27 N) than swimmer A (15 N) in the phase. As stroke technique, the short distance swimmer attempted to maximise hydrodynamic force acting on the hand using more drag in the upsweep phase of the front crawl stroke. Compared to the short distance swimmer, the long distance swimmer used a greater amount of propulsive lift force in the upsweep phase of the front crawl stroke to swim more efficiently. Swimmer A moved the hand more backward during the stroke while swimmer B moved the hand more diagonally during the stroke.

Over the one stroke, swimmers A and B used both propulsive drag and lift (Figure 1). In the downsweep/outsweep phases, the propulsive lift was dominant force for the propulsion in both strokes. This is because the hand moved in the lateral and vertical direction during the phases while the hand still moved forward. In the insweep and upsweep phases, the propulsive drag was inversely proportional to the propulsive lift as either propulsive drag or lift increased. This is because an angle to maximise drag force is not to maximise lift force, and vice versa. Also the swimmer needs to sweep the hand fast in the $x$-direction to increase the hand propulsive drag while in the $yz$-plane to increase the hand propulsive lift.

The present study described the similarities and differences in stroke technique to exert hand propulsion between the front crawl stroke and the butterfly. There were similarities between the front crawl stroke and the butterfly: 1) the swimmers exerted greater non-propulsive force in the upsweep phase than the insweep phase, 2) the swimmers exerted greater propulsion in the insweep phase than the upsweep phase, 3) the swimmers used either propulsive drag or lift as the dominant propulsion in the insweep and upsweep phases, and 4) the hand speed in the insweep phase of the
front crawl stroke was similar to the speed for the butterfly. There were differences between the front crawl stroke and the butterfly; 1) in the insweep phase, the swimmers exerted greater propulsive drag than propulsive lift in the front crawl stroke while exerted a similar amount of propulsive drag to propulsive lift in the butterfly, 2) the hand speed in the upsweep phase of the butterfly was faster than the speed for the front crawl stroke, and 3) the angle of attack in the front crawl was greater than that in the butterfly. The findings in the present study need to be investigated further to determine whether the results might be generalised to all swimmers.

References

Three different calculations to compute a swimmer’s instantaneous active drag profile and variations in the parameter values that arise as a consequence

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1Australian Institute of Sport, ACT

Introduction
The Australian Institute of Sport has developed a free swim analysis system called the Assisted Towing Method (ATM), designed to estimate a swimmer’s instantaneous whole body active drag force profile at the swimmer’s maximum swim velocity. From the swimmer’s active drag profile and acceleration profile, the propulsive force profile may also be computed (Mason et al. 2012). The resultant or net force profile for the swimmer may then be computed as the sum of both the predominantly negative active drag and the predominantly positive propulsive force profile. These three profiles may then be used to assist in the biomechanical assessment of the swimmer’s free swimming technique. Two major research systems have previously investigated the active drag experience by a swimmer. The first of these was the Measurement of Active Drag (MAD) system in which the swimmer pulled on levers under the water to propel himself. The levers were mechanically linked to a force transducer.
(Toussaint et al. 2004). This provided a mean propulsive force value which automatically equated to a mean active drag force value. The second system developed was the velocity perturbation method (VPM) in which the swimmer swam twice at maximum speed, once towing and being resisted by a hydrodynamic body and then again without the hydrodynamic body attached (Kolmogorov et al. 1992). Through a computation using the two mean swim velocity values and the mean resistance force value of the hydrodynamic body, a mean active drag force value at the swimmer’s maximum swim velocity was able to be computed.

The ATM method involves towing the swimmer at a five to eight percent greater speed than the swimmer’s maximum swimming velocity, utilising a tow which allows a swimmer’s natural intra stroke velocity fluctuations to occur. The swimmer must apply equal mean maximum power and use a similar swimming technique in both the assisted swim with the tow and the unassisted swim, as well as maintain a mean constant speed throughout both conditions. The varying drag force as measured with the force platform and the two varying velocity profiles obtained from the dynamometer are used in the computation of active drag. The drag force and velocity parameters are sampled over four freestyle strokes, commencing with a right hand entry after the swimmer has attained the set mean tow velocity. A cubic function obtained by using the maximum swim velocity and the tow velocity is used to compute the swimmer’s active drag parameter by multiplying the drag force profile by this cubic function (Mason et al. 2011). In this research project three different calculations were made. In the first calculation, just the two mean velocities (maximum swim velocity and tow velocity) are used in the calculation (Mason et al. 2013). In the second calculation the two instantaneous variable velocities are used. In the third calculation an additional factor incorporating the acceleration profile is applied to the second calculation.

**Method**

Four elite male freestyle sprint swimmers were tested using the ATM and their active drag parameters were computed using the three different calculations on the data from a single trial. Although the ATM equation to calculate the active drag parameter in the first and second calculation uses the same formula, different velocity values for $V_{assist}$ and $V_{free}$ are used in the calculation (Mason et al. 2013).

![Diagram 1](image)

**Calculation of Active Drag**

$$Da = \frac{F_{tow} \cdot (V_{assist} \cdot V_{free}^3)}{(V_{assist}^3 - V_{free}^3)}$$

In the first calculation, $V_{assist}$ and $V_{free}$ are the mean velocity profile values over the full testing interval where $V_{assist}$ is the mean tow velocity and $V_{free}$ is the maximum mean free swim velocity.

In the second calculation, $V_{assist}$ and $V_{free}$ are the instantaneous varying velocity profile values throughout the full testing interval.
In the third calculation, the swimmer’s acceleration profile is included as part of the calculation and this results in a change in the formula for the instantaneous active drag parameter (Mason et al. 2013).

\[
Da = ma \cdot \frac{(V\text{assist} \cdot V\text{free}^2 - V\text{free}^3) - (F\text{tow} \cdot V\text{assist} \cdot V\text{free}^2)}{(V\text{assist}^2 - V\text{free}^2)}
\]

The formula variables are:

\( Da \) = active drag parameter values
\( Ftow \) = drag force profile values as measured by the force platform
\( V\text{assist} \) = tow velocity profile values as measured by dynamometer
\( V\text{free} \) = free swim velocity profile values computed from \( V\text{assist} \)
\( a \) = acceleration profile values (derivative of \( V\text{assist} \) profile)
\( m \) = inertia of swimmer (mean passive drag value at max swim velocity)
NB. \( V\text{free} \) velocity profile for assisted trials is identical in shape to the \( V\text{assist} \) velocity profile but is reduced overall by a value equal to (Mean of \( V\text{assist} \) – Mean of \( V\text{free} \)).

**Calculation of Propulsive Force**

\( V\text{free} \) (free swim velocity profile), \( Da \) (active drag) and \( P \) (propulsion) all vary throughout the stroke cycle. However there is a relationship between all three.

\[
V\text{free} = \int \frac{P + Da}{m} \, dt
\]

\[
m \cdot V\text{free} = \int P \, dt + \int Da \, dt
\]

\[
\int P \, dt = m \cdot V\text{free} - \int Da \, dt
\]

Since \(
\frac{d}{dt}\int P \, dt = P
\)

Then \[
P = \frac{d}{dt}(m \cdot V\text{free}) - \frac{d}{dt}\int Da \, dt
\]

\[
\therefore \text{Propulsion} = \frac{d}{dt}(m \cdot V\text{free}) - Da
\]

\( V\text{free} \) = Velocity Profile (a function of time) positive value

\( Da \) = Active Drag Profile (a function of time) negative – As \( P \) and \( Da \) directly oppose one another the \( Da \) is considered negative and velocity as positive in the direction of propulsion.

\( P \) = Propulsion Profile (a function of time) predominantly positive values

\( m \) = Inertial force (the mean constant Passive drag force at maximum swimming speed)

**Resultant** (or net) Force = **Active Drag Force** + **Propulsion Force** Where Active drag is predominantly negative and Propulsive force is predominantly positive.
**Analysis**

The three active drag, propulsive force and resultant force profiles for each subject in a single trial were computed using the three different calculation methods. Comparisons were made within each subject between each of the three force profiles (active drag, propulsive force and resultant force) to identify similarities and differences that occurred between the three calculating methods.

**Results**

The results obtained were consistent over all four subjects. The mean active drag and mean propulsive force values were very similar for all three calculations. There were only very slight variations in the active drag, propulsive force and resultant force parameters using the first two calculations. The third calculation resulted in a much larger range in values for the active drag parameter that became excessively positive at its peaks. This resulted in a consequential reduction in the range of the propulsion force parameter. The resultant or net force parameter remained essential the same using all three calculations.

The graphic results, illustrating the relationship between the Active Drag Profile, the Propulsive Force Profile and the Resultant Force Profile are provided for one particular swimmer (swimmer # 1) as an example of what the three calculations resulted in for a particular trial. The mean for both the Active Drag and the Propulsive Force is also included in the graph. The three force profiles within all four swimmers have a similar relationship to one another as is the case illustrated by swimmer #1.

![Graph of Active Drag, Propulsive Force, Resultant Force Profiles](image1)

**Figure 1**  
Mean velocity values are used in the calculation of Active Drag

![Graph of Instantaneous Velocity Profiles](image2)

**Figure 2**  
Instantaneous velocity values are used in the calculation

Note that the profiles in Figures 1 & 2 are essentially close to being identical.
Note that the profiles in Figure 3 are distinctly different from those in Figures 1 & 2.

**Figure 3**  
Acceleration is included as an additional term within the second calculation.

**Figure 4**  
Tow Velocity and Acceleration profiles. Acceleration in m/s² and Tow Velocity in m/s.

**Table 1**  
Lists the Mean Values for active drag and propulsive force for each swimmer.

<table>
<thead>
<tr>
<th>Subject #</th>
<th>One</th>
<th>Two</th>
<th>Three</th>
<th>Four</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation #1</td>
<td>Mean Active Drag (N)</td>
<td>-137</td>
<td>-80.3</td>
<td>-114.2</td>
</tr>
<tr>
<td></td>
<td>Mean Propulsive Force (N)</td>
<td>133.8</td>
<td>80.6</td>
<td>115</td>
</tr>
<tr>
<td>Calculation #2</td>
<td>Mean Active Drag (N)</td>
<td>-137.4</td>
<td>-81.4</td>
<td>-115.2</td>
</tr>
<tr>
<td></td>
<td>Mean Propulsive Force (N)</td>
<td>134.2</td>
<td>81.7</td>
<td>115.9</td>
</tr>
<tr>
<td>Calculation #3</td>
<td>Mean Active Drag (N)</td>
<td>-138.4</td>
<td>-81.3</td>
<td>-114.9</td>
</tr>
<tr>
<td></td>
<td>Mean Propulsive Force (N)</td>
<td>135.2</td>
<td>81.6</td>
<td>115.7</td>
</tr>
<tr>
<td></td>
<td>Mean Tow Velocity (m/s)</td>
<td>2.01</td>
<td>2.1</td>
<td>2.05</td>
</tr>
</tbody>
</table>

Nb. There is very little difference for all the 3 calculations within each parameters for each subject.
Table 2  Lists the range of values for active drag, propulsive force and resultant force

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Calculation #1</th>
<th>Calculation #2</th>
<th>Calculation #3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Active Drag range of values (N)</td>
<td>Propulsive Force range of values (N)</td>
<td>Resultant Force range of values (N)</td>
</tr>
<tr>
<td></td>
<td>436</td>
<td>340</td>
<td>661</td>
</tr>
<tr>
<td></td>
<td>345</td>
<td>280</td>
<td>520</td>
</tr>
<tr>
<td></td>
<td>370</td>
<td>572</td>
<td>880</td>
</tr>
<tr>
<td></td>
<td>481</td>
<td>518</td>
<td>888</td>
</tr>
<tr>
<td></td>
<td>432</td>
<td>374</td>
<td>661</td>
</tr>
<tr>
<td></td>
<td>364</td>
<td>304</td>
<td>520</td>
</tr>
<tr>
<td></td>
<td>358</td>
<td>607</td>
<td>880</td>
</tr>
<tr>
<td></td>
<td>471</td>
<td>540</td>
<td>888</td>
</tr>
</tbody>
</table>

Note that within each subject very little difference occurs between the results of calculation #1 & #2.
Note that the active drag and propulsive force is markedly different when using calculation #3 as opposed to the results from calculation #1 and #2.
Note that all the resultant force values within each subject are identical for all calculation methods.
Note that with calculation #3, the range in values for active drag has been greatly increased while the range for the propulsive force has decreased in comparison to the results from calculation #1 and #2.

Conclusion

As a consequence of the third calculation producing extensive positive values in the active drag parameter at the peaks, the researchers would advise only using the first two calculation methods. Possibly using the second calculation method that utilises varying velocity values rather than mean velocity values is possibly the most desirable.

Discussion

The MAD and the VPM methods of assessing active drag produce only a single value for the mean active drag of the swimmer over the set swimming interval. The ATM on the other hand provides not only the mean active drag value but the entire active drag continuous force profile together with the propulsion force profile and the resultant force profile of the swimmer at the swimmers maximum swim speed. These profiles when provided in conjunction with the side and front on video image of the swimming action are a valuable diagnostic tool to identify inefficiencies in the free swim stroke technique of elite swimmers. Whereas the MAD system actually measures rather than estimates the mean active drag value both the VPM and ATM systems estimate the active drag parameter based on certain assumptions. These assumptions include: that the swimmer applies maximum power in all swim tests, that the swimmer maintains a constant mean swim velocity and uses similar swim technique in all tests, that the velocity of the hip is representative of the velocity of the swimmer's centre of gravity and that at the swimmer's top swimming speed (from 1.6 to 2.0 m/s) that active drag is considered close to a function of swim velocity squared. A major criticism associated with the MAD system is the degree to which the actions of the swimmer being tested resemble that of the actual swimming technique of the swimmer. However a definite benefit of the MAD system is that it provides mean active drag force values over a range of swim velocities. It is obvious from the above that the ATM method of estimation has advantages over the MAD and VPM systems. This particular research project was performed to identify which of the three possible calculations should be used to estimate the active drag force profile of the swimmer using the ATM method.

References


Longitudinal and confirmatory assessment of young swimmers’ performance and its determinant factors

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Keywords: modelling, age-group swimmers, performance, efficiency, kinematics, hydrodynamics

Introduction

Latent growth curve modeling is a structural equation modeling technique for longitudinal dataset. It is a confirmatory data analysis procedure to learn about the variations of an endogenous variable over time. The technique is characterised by estimating intra- and inter-individual growth trajectories enabling researchers to predict future development. This modelling procedure has been applied in other scientific fields, such as Social Sciences but never attempted before in Sport Sciences or sports performance as much as we are aware of. Indeed, all structural equation models reported in the sports performance literature were developed from cross-sectional data (e.g. Morais et al. 2012; Barbosa et al. 2010).

Swimming performance is a multi-factorial phenomenon, where the interactions between several exogenous variables determine the endogenous one. Young swimmers’ performance is strongly related to the kinematics (e.g. Lätt et al. 2009; Morais et al. 2012) and hydrodynamics (e.g. Toussaint et al. 1990; Marinho et al. 2010; Saavedra et al. 2010). A few follow-up and tracking studies suggested that at different moments of a season, performance would be mostly dependent from different determinant factors (e.g. Morais et al. 2013). Nevertheless, until now such relationship was never modeled.

The aim of this research was to compute a latent growth curve model for young swimmers’ performance and its biomechanical determinant factors. It was hypothesised that different exogenous variables would have the main direct effect on the performance improvement (endogenous variable) over time.

Methods

Sample. Thirty young swimmers (14 boys: 12.33±0.65 years-old; and 16 girls: 11.15±0.55 years-old; both genders in Tanner stages 1-2 by self-report at baseline) were monitored during a competitive season. The swimmers had at the beginning of the season 3.40±0.56 years of training experience (training sessions per week: 5.09±0.87) and have participated on regular basis in regional and national level competitions. Coaches, parents and/or guardians and also the swimmers gave their consent for participation on this study. All procedures were in accordance to the Helsinki Declaration regarding Human research. The University Institutional Review Board also approved the study design.

Study design. Swimmers were evaluated immediately before the beginning of the season (M1-baseline), 4 weeks after the beginning of the season (M2); in the middle (M3) and at the end of the
season (M4). Theoretical model was designed to determine young swimmers’ performance based on kinematics, hydrodynamics and efficiency variables according to what was reported before in the literature (e.g. Barbosa et al. 2010; Marinho et al. 2010) (figure 1).

Figure 1   Theoretical latent growth curve model

Performance data collection. The official time of the SCM 100-m freestyle race was selected as a performance outcome (less than two weeks between official race and data collection) (Barbosa et al. 2010).

Kinematic and efficiency data collections. Swimmers performed 3 maximal trials of 25-m at Front Crawl with a push-off start. A speedo-meter cable (Swim speedo-meter, Swimsportec, Hildesheim, Germany) was attached to the swimmers’ hip. A 12-bit resolution acquisition card (USB-6008, National Instruments, Austin, Texas, USA) was used to transfer data (sampling rate at 50Hz) from the speedo-meter to a software designed and developed by our group (LabVIEW® interface, v.2009) (Barbosa et al. 2013). Data were exported to a signal processing software (AcqKnowledge v.3.9.0, Biopac Systems, Santa Barbara, USA) and filtered with a 5Hz cut-off low-pass 4th order Butterworth filter. Speed fluctuation was computed as (Barbosa et al. 2013):

$$dv = \frac{\sum_i (v_i - \bar{v})^2 F_i/n}{\sum_i v_i F_i/n}$$

(1)

Where dv is the speed fluctuation, v is the mean velocity, vi is the instant velocity, Fi is the absolute frequency and n is the number of observations. The arm’s propelling efficiency was estimated as (Zamparo et al. 2005):

$$\eta_p = \left(\frac{v^2 - 0.9}{2 \cdot SF \cdot l}\right) \cdot \frac{2}{\pi} \cdot 100$$

(2)

Where ηp is the propelling efficiency, v is the velocity, SF is the stroke frequency and l is the distance between shoulder and tip of the 3rd finger during the insweep. Stroke frequency was measured with a chrono-frequency counter during three consecutive strokes by two expert evaluators (ICC = 0.96).

Hydrodynamic data collection. Two extra maximal trials were performed to assess the hydrodynamic profile with the Velocity Perturbation Method (Kolmogorov and Duplisheva 1992). One trial with and another without carrying on the perturbation device were performed by the swimmers. Two expert evaluators measured with stopwatches the times between the 11th and 24th meter (ICC = 0.98) (Marinho et al. 2010). Active drag was computed as (Kolmogorov and Duplisheva 1992):
\[ D_a = \frac{D_b \nu_b \nu^2}{\nu^2 - \nu_b^2} \]  
\[ C_{D_a} = \frac{2D_a}{\rho S \nu^2} \]

Where \( D_a \) is the swimmers’ active drag at maximal velocity, \( D_b \) is the resistance of the perturbation buoy, \( \nu_b \) and \( \nu \) are the swimming velocities with and without the perturbation device, respectively. Coefficient of active drag was calculated as (Kolmogorov and Duplisheva 1992):

\[ P_{\text{d}} = D \cdot \nu \]

Where \( P_{\text{d}} \) is the power to overcome drag, \( D \) is the drag force and \( \nu \) is the velocity.

**Modelling procedures.** The normality and homoscedasticity assumptions were analyzed with the Shapiro-Wilk and the Levene tests. Performance variation was computed with latent growth curve modeling (i.e., longitudinal structural equation model). It was used the path-flow analysis model to perform the estimation of linear regression standardised coefficients between exogenous (i.e. kinematic, hydrodynamics and efficiency parameters) and endogenous variable (i.e. performance). Standardised regression coefficients (\( \beta \)) were considered, and its significance assessed with the Student’s t-test (ps0.05). The intercept and slope are latent variables that are not directly observed but rather inferred. The intercept determines where the participant baseline is and how they differ in that specific moment (i.e. it shows the inter-individual differences between the participants at the baseline, corresponding to M1 in this model). The slope is the average rate of growth (i.e. variation over time) between the first and last evaluation moment. To measure the quality of the models’ good-of-fit, it was computed the ratio Chi-square/degrees of freedom (\( x^2/df \)). It was considered qualitatively if (Wheaton 1987): 5 < \( x^2/df \) poor adjustment; 2 < \( x^2/df \) ≤ 5 reasonable adjustment; 1 < \( x^2/df \) ≤ 2 good adjustment; \( x^2/df \) ~1 very good adjustment.

**Results**

Performance improved significantly between M1 and M4. In M2 and M3, performance achieved 59% and 99% of the last moment (M4), with significant differences between both moments (P < 0.001) (Figure 2). The intercept was significant for all models suggesting a high inter-individual variability at the baseline. The \( \eta_p \) model presented the highest path (\( \beta = 28.15; P < 0.001 \)). The slope was also significant for all models. These data shows a high variance between swimmers in the performance growth, being the dv model the one with the highest path (\( \beta = 6.56; P < 0.001 \)).

Overall the selected exogenous variables showed significant direct effects on the endogenous variable (i.e. performance). The \( D_a \) (in M1: \( \beta = -0.62; P<0.001 \) and; M2: \( \beta = -0.53; P<0.001 \); figure 2E), \( \eta_p \) (in M3: \( \beta = 0.59; P<0.001 \); figure 2C) and SF (in M4: \( \beta = -0.57; P<0.001 \); figure 2A) were the exogenous variables with highest contributions. Hence, swimmers relied in different exogenous variables to enhance the performance in different moments of the season.

Gender had a significant effect in the baseline performance (i.e. M1; intercept) and also in the performance growth over time (i.e. slope; between M1 and M4). Boys presented better performances than girls at M1 (models ranging between \( \beta = 0.88; P<0.001 \) and \( \beta = 0.94; P<0.001 \)). As for the slope, all paths from gender were also significant for all models (ranging between \( \beta = 0.56; P<0.001 \) and \( \beta = 0.86; P<0.001 \)). The models’ good-of-fit ranged between 1.40sx^2/dfs\leq3.74 (i.e. good-reasonable).
A: SF – stroke frequency; B: dv – speed fluctuation; C: ηp – arm’s propelling efficiency; D: CDa – coefficient of active drag; E: Da – active drag; F: Pd – power to overcome drag; ICEPT – intercept effect; SLOPE – slope effect; Gender – gender effect; yi → yi – variable yi depends from variable xi.

Figure 2 Growth confirmatory models for performance and variables selected

Discussion
The aim of this research was to compute a latent growth model to explain young swimmers’ performance and its determinant biomechanical factors. Main finding was that during the competitive season different biomechanical variables had a significant contribution to the performance growth.

Latent growth curve modeling showed that young swimmers’ performance improved significantly between M1 and M4. The added value of this procedure is that it provides the amount of
performance achieved in each evaluation moment. In M2 young swimmers achieved 59% of the total performance in M4. Young swimmers experienced a detraining period (i.e. summer break) impairing energetics and kinematics (Moreira et al., in press). Therefore this performance improvement in M2 might be related with a high training volume at the first stage of the competitive season, building-up energetics. The rate of performance improvement decrease between M2 and M3 (39%) as well as M3 and M4 (1%). As happens with adult/elite swimmers, younger counterparts also improve performance in a less sharp way as they get closer to the season major competition.

Furthermore, latent growth curve modeling also highlights the existence of inter- and intra-individual variability. Dynamic systems theory and non-linear analysis, stresses out that variability should not be considered as random error and therefore not ignored in the overall analysis (Davids et al. 2003). Young swimmers’ performance significantly differed in M1 (high variability in the intercept) and also during the performance growth (high variability in the slope). This confirms age-group swimming as a multi-factorial phenomenon. Growth and maturation influence young swimmers’ kinematics and hydrodynamics. At these early ages each swimmer has his own rate of growth and maturation, leading to a very unique and inter-individual variability (Morais et al. 2013).

Being swimming a multi-factorial sport, characterised by an interplay of several features, it was hypothesised that different variables would have a higher contribution to performance in each evaluation moment. Latent growth curve provides this kind of information as it analyzes the contribution of exogenous variables to the endogenous one (i.e., performance). In M1 and M2, the $D_a$ was the main performance determinant. Young swimmers’ training should be focused on technical enhancement (Morais et al. 2012; Barbosa et al. 2010). It seems that in the two first evaluation moments the hydrodynamic features were the main determinants to enhance performance. Nevertheless the increase in the $D_a$ might be also related with the increase in the swimming velocity that young swimmers achieved to enhance their performance.

In M3 and M4 the stroke mechanics were the performance main determinants. The $\eta_p$ was the biggest contributor to the performance improvement in M3. Indeed the swimmers achieved the highest mean value for the $\eta_p$ in M3. Coaches could put the focus on the energetic build-up or the technique improvement. But for young swimmers, it seems that 50% to 60% of the performance enhancement relies on the technique/biomechanics (Morais et al. 2012). In M4 the SF presented the highest path and therefore the biggest contribution. At least for post-pubertal swimmers strength & power are related to SF (Giroud et al. 2007). One might speculate that over the season, our subjects build-up strength & power, which had an effect on the SF.

For all models a gender effect was verified for both intercept (i.e. baseline; M1) and slope (i.e. performance growth; between M1 and M4). There is solid evidence in the literature about a gender gap for body dimensions and biomechanical features. E.g., Barbosa et al. (2013) showed that peripubertal boys have a higher $D_a$ (hydrodynamics), $dv$ and SF (kinematics) than girls. Latent growth curve modeling also revealed that gender gap. So, this modelling solution is sensitive to these aspects. Hence, it can be used when subjects of different competitive levels or other key-features are pooled in one single sample.

Overall, data shows that the improvement of young swimmers’ performance relies on the contribution of different variables during a given time-frame. Both hydrodynamics and kinematics had a significant contribution to performance. This suggests that coaches should put the focus on the technique and efficiency training.

**Conclusions**

Latent growth curve modeling is a comprehensive technique to gather insight about the relationships between young swimmers’ performance and its determinant factors over a season. Young swimmers relied on different biomechanical variables to enhance the performance in different moments of the season.
Acknowledgments

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References


External kinetics measurements in individual and relay swimming starts: a review

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Keywords: biomechanics, forces, moments, swimming analysis, starting techniques

This study aimed to present a literature review on the external kinetics of swimming starts for the purposes of summarising and highlighting existing knowledge, identifying gaps and limitations and challenging new researchers for future projects. A preliminary literature search was performed using
relevant electronic databases, only for English written documents published before September 2013. Keywords including ‘swimming’ and ‘start’ were used to locate documents. Proceedings of the scientific conferences of Biomechanics and Medicine in Swimming (BMS) and the International Society of Biomechanics in Sports (ISBS) from 1970 and 1983, respectively, to 2013 were examined. Included studies were experimental biomechanical approaches in laboratory setting relating to external kinetics assessments on swimming starts. Twenty-eight studies were included in this review, of which 10 are peer-review journal articles and 18 are proceedings from the BMS and ISBS Congress series. From the overall included studies, 82.14% analysed the individual ventral starts, followed by 14.28% at backstroke and only 3.57% at relay starts. Twenty-five per cent from the overall ventral starting studies measured the external horizontal and vertical forces acting on the swimmer’s hands and only one research group has yet published about the upper limbs horizontal force on the backstroke start. Previous studies have presented unique contribution in swimming start kinetics; however, future researches should focus on devices capabilities improvements based on the current starting block configuration, mainly for dorsal and relay starting kinetics analysis purposes, and considering three dimensional, 6 degrees of freedom analysis of the forces exerted by each of the four limbs.

Introduction

The swimming start, defined by the time period between the starting signal until the swimmer’s head achieve 15 m (e.g. Vantorre et al. 2010), is an important part of short and middle distance swimming events. For example, 15 m after the start, the second-placed at men’s 100 m freestyle at Barcelona 2013 Swimming World Championships was 0.08 s slower than the winner, and the final race time difference was only 0.11 s. The importance of the start is emphasised further in middle distance events, since, in the same swimming competition, the winner at men’s 200 m freestyle performed the fastest 15 m starting time during the final. In fact, at the recent elite level swimming competitions it is not the swimming speed that wins races but rather the better technicians in starts and also turns (Mason et al. 2012).

The swimming start is composed of several phases (block/wall, flight, entry, glide, leg kicking and swimming) (Slawson et al. 2013; Vantorre et al. 2010), which are interdependent (Vantorre et al. 2010). According to Guimarães and Hay (1985) and Mason et al. (2007), the block phase determines what happens in flight and subsequently the underwater phase, respectively. Vantorre et al. (2010) have verified that the block phase negatively correlated with the starting time and advised swimmers to perform a rapid reaction to the starting signal and impulse over the starting block. In fact, the study of the ground reaction forces, which generate the swimmers’ movements that attend such above-mentioned requirements have been conducted since the 70s. To date, Elliot and Sinclair (1971) were the pioneer on the starting block instrumentation for direct force measurements.

Despite the well accepted relevance of the external kinetics assessment and understanding at swimming starts, no former review was found in the literature about the different dynamometric devices and respective parameters assessed. It would be interesting to find scientific evidence and report the advancements pertaining to the direct forces measurement in individual and relay swimming starts. Considering that the international swimming rules for individual and relay starting recommendations have changed, and the starting block has undergone many adaptations, it is crucial to gather the most relevant studies in a synthesised critical review. This study reviewed the swimming literature on starting external kinetics for the purposes of summarising and highlighting existing knowledge, identifying gaps and limitations and challenging new researchers for future projects.

Methods

A preliminary literature search was performed using PubMed, SportDiscus, Scopus and ISI Web of Knowledge electronic databases, only for English written documents published before September 2013. Keywords including ‘swimming’ and ‘start’ were used to locate documents. Proceedings of the scientific conferences of Biomechanics and Medicine in Swimming (BMS) and the International
Society of Biomechanics in Sports (ISBS) from 1970 and 1983, respectively, to 2013 were examined. Included studies were experimental biomechanical approaches in laboratory setting relating to external kinetics assessments on swimming starts. The documents that were available only as abstracts and duplicated studies were excluded.

**Results**

Table 1 display the ultimately 28 studies included in this review, of which 10 are peer-review journal articles and 18 are proceedings from the BMS and ISBS Congress series. Twenty-five and 46.42% from the overall starting studies applied the strain gauges and piezoelectric crystals technology, respectively. From the overall included studies, 82.14% analysed the individual ventral starts, followed by 14.28% at backstroke and only 3.57% at relay starts. Twenty-five per cent from the overall ventral starting studies measured the external horizontal and vertical forces acting on the swimmer’s hands. Only one research group has yet published about the upper limbs horizontal force on the backstroke start. Researchers have instrumented the handgrips with load cells or bonded strain gauges directly to the hands bar to measure the overall upper limbs force. To measure the horizontal and resultant lower limbs external kinetics at backstroke starting, researchers have used one force plate, while for ventral starts one and two force plates have been mounted over the starting block to measure mainly the horizontal and vertical reaction force components. Despite most of the research groups have used three-dimensional sensors, only two have studied the lateral force component action on the swimmers’ lower limbs. Moments of force and centre of pressure were assessed once at individual ventral start.
Table 1  The 28 included studies which assessed the external forces in individual ventral and dorsal and relay starts, and the respective general description

<table>
<thead>
<tr>
<th>Authors</th>
<th>Start technique</th>
<th>Forces assessed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elliot and Sinclair (1971)</td>
<td>Ventral</td>
<td>Horizontal lower limbs</td>
</tr>
<tr>
<td>Cavanagh et al. (1975)</td>
<td>Grab</td>
<td>Horizontal and vertical upper limbs</td>
</tr>
<tr>
<td>Stevenson and Morehouse (1978)</td>
<td>Grab</td>
<td>Horizontal and vertical upper limbs</td>
</tr>
<tr>
<td>Shierman (1978)</td>
<td>Grab</td>
<td>Horizontal and vertical lower limbs</td>
</tr>
<tr>
<td>Zatsiorsky et al. (1979)</td>
<td>Arm swing, grab and track</td>
<td>Horizontal and vertical lower limbs</td>
</tr>
<tr>
<td>Hay and Guimarães (1983)</td>
<td>Grab</td>
<td>Horizontal upper and lower limbs</td>
</tr>
<tr>
<td>Vilas-Boas et al. (2000)</td>
<td>Track</td>
<td>Horizontal, vertical and resultant</td>
</tr>
<tr>
<td>Naemi et al. (2000)</td>
<td>Grab</td>
<td>Horizontal and vertical lower limbs</td>
</tr>
<tr>
<td>Krueger et al. (2003)</td>
<td>Grab and track</td>
<td>Horizontal and resultant lower limbs</td>
</tr>
<tr>
<td>Breed and Young (2003)</td>
<td>Grab, track, swing</td>
<td>Horizontal upper and lower limbs</td>
</tr>
<tr>
<td>Vilas-Boas et al. (2003)</td>
<td>Grab and track</td>
<td>Horizontal, vertical lower limbs</td>
</tr>
<tr>
<td>Benjanuvatra et al. (2004)</td>
<td>Grab and track</td>
<td>Horizontal and vertical lower limbs</td>
</tr>
<tr>
<td>Kibele et al. (2005)</td>
<td>Ventral</td>
<td>Horizontal, vertical and resultant</td>
</tr>
<tr>
<td>Arellano et al. (2005)</td>
<td>Grab</td>
<td>Horizontal and vertical lower limbs</td>
</tr>
<tr>
<td>Mason et al. (2007)</td>
<td>Grab</td>
<td>Horizontal lower limbs</td>
</tr>
<tr>
<td>Hohmann et al. (2008)</td>
<td>Backstroke</td>
<td>Horizontal and vertical lower limbs</td>
</tr>
<tr>
<td>Galbraith et al. (2008)</td>
<td>Track and one handed track</td>
<td>Horizontal lower and vertical upper and lower limbs</td>
</tr>
<tr>
<td>Vint et al. (2009)</td>
<td>Track</td>
<td>Horizontal upper limbs</td>
</tr>
<tr>
<td>de Jesus et al. (2010)</td>
<td>Backstroke</td>
<td>Horizontal lower limbs</td>
</tr>
<tr>
<td>Vantorre et al. (2010)</td>
<td>Grab</td>
<td>Horizontal and vertical lower limbs</td>
</tr>
<tr>
<td>Takeda et al. (2010)</td>
<td>Relay</td>
<td>Horizontal lower limbs</td>
</tr>
<tr>
<td>Cossor et al. (2011)</td>
<td>Track</td>
<td>Horizontal and vertical lower limbs</td>
</tr>
<tr>
<td>de Jesus et al. (2011)</td>
<td>Backstroke</td>
<td>Horizontal lower and upper limbs</td>
</tr>
<tr>
<td>Kilduffi et al. (2011)</td>
<td>Ventral</td>
<td>Horizontal and vertical lower limbs</td>
</tr>
<tr>
<td>Slawson et al. (2011)</td>
<td>Track</td>
<td>Horizontal and vertical lower limbs</td>
</tr>
<tr>
<td>Honda et al. (2012)</td>
<td>Track and kick</td>
<td>Horizontal vertical and resultant, vertical upper limbs</td>
</tr>
<tr>
<td>de Jesus et al. (2013)</td>
<td>Backstroke</td>
<td>Horizontal lower and upper limbs</td>
</tr>
<tr>
<td>Slawson et al. (2013)</td>
<td>Kick</td>
<td>Horizontal and vertical lower limbs</td>
</tr>
</tbody>
</table>

Discussion

The external force assessments during swimming starts are considered of great value for coaches and swimmers, since they provide information about how swimmers’ movements are generated to propel themselves out of the starting block. The findings of this study evidence that swimming researchers have been very concerned about the external kinetics assessment at individual ventral starts, and have optimised the devices according to the starting rule changes for block configuration (FINA, FR 2.7). However, much effort should be invested to the study of the upper limbs dynamometry, mainly considering all the possibilities allowed by the FINA regulations, as performed by Vint et al. (2009) with instrumented front and side handgrips. Researchers should also consider the implementation of force sensors in lateral handgrips to knowledge about the dynamometric profile used at the tuck starting technique.

In contrast to the substantial quantity of studies which approach kinetics at individual ventral starts, there is a paucity of backstroke start kinetic data, mainly due to the technical difficulties associated with the adaptation of the kinetic devices to the starting block and pool wall (c.f. de Jesus et al. 2011, 2013). Despite the considerable contribution provided by the previous studies, a large effort should be invested to adapt the kinetic devices according to the actual starting block configuration, as implementing the two horizontal and lateral backstroke start handgrips. Considering the individual
ventral and dorsal starts, the relay techniques have received much less attention, since only one research group has attempted to analyze the horizontal ground reaction force component in three different techniques (c.f. Takeda et al. 2010). Further research should be conducted including the rear back plate to verify if swimmers change the respective force profiles when performing relay starts using this recent authorised device.

The consistent use of three dimensional force sensors has been implemented mainly to study the horizontal (antero-posterior) and vertical upper and lower limbs force components. In fact, the major and relevant components are the forces applied in the vertical and antero-posterior axes (Slawson et al. 2013); however, the medio-lateral axis was studied by Vantorre et al. (2010) in elite and trained swimmers, and might be considered an important feedback to improve technique and performance of young swimmers.

**Conclusion**

The external forces assessment during starts is an important concern of the swimming research community. Researchers have continually adapted the instrumented starting block to measure upper and lower limbs forces, mainly at individual ventral starts. However, sports biomechanics and engineers should invest effort to develop a 3D kinetic system based on the actual block configuration capable to identify the upper and lower limbs contribution to propel starters out of the block/wall at different starting techniques.

**Acknowledgments**

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Cavanagh, P.R., Palmgren, J.V., Kerr, B.A. (1975). A device to measure forces at the hands during the grab start, In: L. Lewillie, J.P. Clarys (Eds.), Swimming II, pp. 43-50


**Elliptic model for evaluation of tumble turn in swimming**

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**Keywords:** tumble turn, elliptic model, inclination, major axis, minor axis

The purpose of this study was to evaluate the tumble turn in swimming based on an elliptical model. Fifteen junior male swimmers were asked to perform 15 m round trip crawl including a tumble turn as fast as possible. A side view of the turn was analysed by the 2D-DLT algorithm. The trajectory of the head during the rotation phase was approximated by an elliptic model (r >= 0.90). The correlation between the elliptic indices and 15 turn properties were calculated. These elliptic indices were as follows: the inclination showed 65.9 ± 7.0 deg, the major axis indicated 0.51 ± 0.08 m, and the minor axis was 0.34 ± 0.10 m. The inclination significantly correlated with the 15m turn-out time 7.72 ± 0.36 sec (r = 0.795, p < 0.01). The minor axis significantly correlated with the 3 m turn-in time 2.21 ± 0.12 sec (r = 0.569, p < 0.05). It was suggested that a shallower inclination and flattened of the elliptic trajectory of the head during the rotation phase had advantageous to turn performance.

**Introduction**

A rule about the turns of the freestyle of competitive swimming race is ‘Some part of the swimmer must touch the wall upon completion of each length and at the finish.’ in FINA Rules (FINA 2013). Typically in freestyle, tumble turn is to finish one length and begin the next as fast as possible. Tumble turn has developed by Robertson, J.W. and Kiefer, A. in the 1930s. (Jones 2009). Much research on biomechanical involved tumble turn performance had been made so far. Nicol and Krüger (1979) analysed the flip turn and the open turn used in freestyle swimming. The summation of forward swimming time, duration of impulse, and return swimming time from the wall to 3m of the flip turn was significantly shorter than that of the open turn. During the flip turn, velocity is maintained, but the kinetic energy changes. The locomotion of the body changes to the rotation before push off. Hay (1985) settled the relationships between the turning time and the factors that determine. When this concept is modified for the tumble turn, it is classified roughly in turn-in phase, wall contact phase, and turn-out phase. The turn-in phase is subdivided into approach phase and rotation phase. The turn-out phase is composed of glide phase and stroke preparation phase. Blanksby et al. (1996) studied the tumble turn of age-group swimmers using a force plate and two underwater video cameras. The 5m round trip time (RTT) correlated with peak force, wall contact time (WCT), impulse, tuck index, turn start time, swim resumption distance and peak speed. Lyttle et al. (1999) investigated kinetics in the freestyle tumble turn push-off. It was the result that the CG velocity of after leaving the wall was multiple regressed by the push-off time, the peak drag force and peak propulsive force. Puel et al. (2012) performed kinematic and dynamic 3D analyses of the front crawl tumble turn in elite male swimmers. The 3m RTT was multiple regressed by the place where rotation starts, the horizontal speed at the force peak, and the 3D length of the path covered during the turn. The wide gap of the head trajectories from the bottom view was 0.2 to 0.3m.

However, there was not observed parameters to evaluate the rotation phase, except the tuck index. The purpose of this study was to evaluate of the tumble turn in swimming based on an elliptic model.

**Methods**

Subjects were 15 junior male freestyle swimmers at the regional level (Height = 1.662 ± 0.075 m, Weight = 55.3 ± 9.5 kg, Age = 14.4 ± 0.8 yrs, FINA point = 526 ± 46). The subjects were asked to perform 15m round trip crawl including a tumble turn as fast as possible. Three cameras were set up at pool side (HDR-UX1, Sony), underwater (WTW-WA7000H, Tsukamoto) and 15m point (HXR-MC1, Sony). Those have been synchronised by the video mixer (V-4, Roland). A side view of the turn was analysed for each swimmer by digitising of the head and other anatomical points. 2D coordinates of sagittal plane were transformed into real space coordinates using a 2D-DLT algorithm with self-made...
motion analysis software named Note Player using Microsoft Excel and Windows API controlled by Visual Basic. The accuracy of the coordinates was evaluated by the difference of the actual value and the estimated value (horizontal = 0.013m, vertical = 0.028m). Butterworth low-pass filter with a cutoff frequency of 8 Hz was used to remove noise from all velocity data.

For the purpose of this study, tumble turn performance was divided roughly in the turn-in, the wall contact, and the turn-out phase. The turn-in phase was subdivided into the approach and rotation phase. The turn-out phase was composed of glide, stroke preparation, and swimming phase. The phase definitions for tumble turn were illustrated in Figure 1.

The trajectory of the head during the rotation phase was approximated by an elliptic model. Since there were a few wide gaps of the head trajectories (Puel et al. 2012), sagittal plane coordinate was analysed in this study. The inclination of the ellipse, major axis and minor axis were optimised to fit these coordinate data by the generalised reduced gradient nonlinear solving method (Lasdon et al. 1978). The conception diagram of the elliptical model was shown in Figure 2.

The temporal and kinematic properties consisted that the turn performance of 2 items, the turn-in phase of 5 items, the contact phase of 4 items, and the turn-out phase of 4 items. These items were computed for each turn, as was shown in Table 1. For example, time factors were 3mRTT that was 3m round trip time of the swimmer’s head that is the turn time from 3m in to 3m out, or WCT that was the wall contact time from first contact to push off; velocity factors were ApV that was the approach horizontal average velocity from 3 m to 1.5 m, or RoV that was the rotation horizontal average velocity from 1.5 m to first contact; distances were RoD that was the head to wall distance at rotation start, or HeadDepth that was the head maximal depth during rotation. Tuck index was the percentage of hip to wall distance at first contact to one at push off. Similarly, Stretch index was the percentage of fingertip to hip distance at first contact to one at push off. Correlation coefficients among the 3 elliptic indices and 15 turn property items were calculated.
This study protocol was approved by the Kyoto Institute of Technology Ethics Committee for Scientific Research Involving Human Subjects.

![Trajectory of the head during the rotation phase fitted to the elliptic model](image)

**Figure 2** Trajectory of the head during the rotation phase fitted to the elliptic model

<table>
<thead>
<tr>
<th>Phase</th>
<th>Item</th>
<th>Unit</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn performance</td>
<td>3mRTT</td>
<td>sec</td>
<td>3m round trip time of the swimmer’s head that is the turn time from 3m in to 3m out.</td>
</tr>
<tr>
<td></td>
<td>3mRTD</td>
<td>m</td>
<td>3m round trip distance of the swimmer’s head trajectory.</td>
</tr>
<tr>
<td>Turn-in Approach</td>
<td>3mTurn-inT</td>
<td>sec</td>
<td>Time required from 3m to first contact.</td>
</tr>
<tr>
<td>Approach</td>
<td>ApV</td>
<td>m/sec</td>
<td>The approach horizontal average velocity from 3m to 1.5m.</td>
</tr>
<tr>
<td>Rotation</td>
<td>RoD</td>
<td>m</td>
<td>The head to wall distance at rotation start.</td>
</tr>
<tr>
<td></td>
<td>RoV</td>
<td>m/sec</td>
<td>The rotation horizontal average velocity from 1.5m to first contact.</td>
</tr>
<tr>
<td></td>
<td>Head Depth</td>
<td>m</td>
<td>The head maximal depth during rotation.</td>
</tr>
<tr>
<td>Contact</td>
<td>WCT</td>
<td>sec</td>
<td>The wall contact time from first contact to push off.</td>
</tr>
<tr>
<td></td>
<td>Foot Depth</td>
<td>m</td>
<td>The foot depth at first contact.</td>
</tr>
<tr>
<td></td>
<td>Tuck Index</td>
<td>%</td>
<td>The percentage of hip to wall distance at first contact to one at push off.</td>
</tr>
<tr>
<td></td>
<td>Stretch Index</td>
<td>%</td>
<td>The percentage of fingertip to hip distance at first contact to one at push off.</td>
</tr>
<tr>
<td>Turn-out</td>
<td>3mTurn-outT</td>
<td>sec</td>
<td>3m time required from push off to 3m.</td>
</tr>
<tr>
<td>Glide</td>
<td>GlV</td>
<td>m/sec</td>
<td>The glide horizontal average velocity from 1.5m to 3m.</td>
</tr>
<tr>
<td></td>
<td>GlAngle</td>
<td>deg</td>
<td>The angle of regression line between foot, knee, hip, shoulder and fingertip at push off.</td>
</tr>
</tbody>
</table>

**Results**

The results of the head trajectory fitted to the elliptical model were shown table 2.
Table 2  The Indices of elliptic model for each subject

<table>
<thead>
<tr>
<th>Sub.</th>
<th>Inclination (deg)</th>
<th>Major axis (m)</th>
<th>Minor axis (m)</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50.5</td>
<td>0.62</td>
<td>0.51</td>
<td>0.99</td>
</tr>
<tr>
<td>2</td>
<td>71.9</td>
<td>0.49</td>
<td>0.30</td>
<td>0.98</td>
</tr>
<tr>
<td>3</td>
<td>57.0</td>
<td>0.67</td>
<td>0.35</td>
<td>0.99</td>
</tr>
<tr>
<td>4</td>
<td>58.8</td>
<td>0.52</td>
<td>0.41</td>
<td>0.99</td>
</tr>
<tr>
<td>5</td>
<td>62.7</td>
<td>0.51</td>
<td>0.27</td>
<td>0.97</td>
</tr>
<tr>
<td>6</td>
<td>67.0</td>
<td>0.62</td>
<td>0.51</td>
<td>0.96</td>
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<tr>
<td>7</td>
<td>67.0</td>
<td>0.46</td>
<td>0.39</td>
<td>0.99</td>
</tr>
<tr>
<td>8</td>
<td>66.2</td>
<td>0.53</td>
<td>0.31</td>
<td>0.90</td>
</tr>
<tr>
<td>9</td>
<td>63.8</td>
<td>0.57</td>
<td>0.41</td>
<td>0.90</td>
</tr>
<tr>
<td>10</td>
<td>66.7</td>
<td>0.55</td>
<td>0.43</td>
<td>0.99</td>
</tr>
<tr>
<td>11</td>
<td>68.4</td>
<td>0.47</td>
<td>0.28</td>
<td>0.99</td>
</tr>
<tr>
<td>12</td>
<td>68.5</td>
<td>0.35</td>
<td>0.13</td>
<td>0.90</td>
</tr>
<tr>
<td>13</td>
<td>70.2</td>
<td>0.46</td>
<td>0.30</td>
<td>0.97</td>
</tr>
<tr>
<td>14</td>
<td>68.8</td>
<td>0.42</td>
<td>0.28</td>
<td>0.99</td>
</tr>
<tr>
<td>15</td>
<td>80.7</td>
<td>0.49</td>
<td>0.22</td>
<td>0.95</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>65.9 ± 7.0</td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td>0.51</td>
<td>0.34</td>
<td></td>
</tr>
</tbody>
</table>

Notes: r showed a correlation of actual and estimated value.

The trajectory of the head during the rotation phase was approximated with high precision by an elliptical model (r >=0.90). The inclination of ellipse showed 65.9 ± 7.0 deg, the major axis indicated 0.51 ± 0.08 m, the minor axis was 0.34 ± 0.10 m.

The results of tumble turn properties and correlation with elliptic indices were shown in Table 3.

Table 3  Temporal and kinematic properties for the tumble turn and Correlation with elliptic indices

<table>
<thead>
<tr>
<th>Phase</th>
<th>Item</th>
<th>Unit</th>
<th>Mean</th>
<th>SD</th>
<th>Inclination</th>
<th>Major axis</th>
<th>Minor axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn performance</td>
<td>3mRTT</td>
<td>sec</td>
<td>3.02</td>
<td>0.11</td>
<td>0.263</td>
<td>0.050</td>
<td>0.135</td>
</tr>
<tr>
<td></td>
<td>3mRTD</td>
<td>m</td>
<td>4.87</td>
<td>0.27</td>
<td>-0.384</td>
<td>0.757</td>
<td>0.682 **</td>
</tr>
<tr>
<td>Turn-in Approach</td>
<td>3mTurn-inT</td>
<td>sec</td>
<td>2.21</td>
<td>0.12</td>
<td>-0.157</td>
<td>0.274</td>
<td>0.569 *</td>
</tr>
<tr>
<td></td>
<td>ApV</td>
<td>m/sec</td>
<td>1.63</td>
<td>0.11</td>
<td>-0.186</td>
<td>-0.033</td>
<td>-0.153</td>
</tr>
<tr>
<td></td>
<td>RoD</td>
<td>m</td>
<td>1.15</td>
<td>0.12</td>
<td>0.028</td>
<td>0.162</td>
<td>-0.142</td>
</tr>
<tr>
<td>Rotation</td>
<td>RoV</td>
<td>m/sec</td>
<td>1.17</td>
<td>0.08</td>
<td>0.336</td>
<td>-0.334</td>
<td>-0.625 *</td>
</tr>
<tr>
<td></td>
<td>Head Depth</td>
<td>m</td>
<td>-0.59</td>
<td>0.05</td>
<td>0.540</td>
<td>* -0.766 **</td>
<td>-0.477</td>
</tr>
<tr>
<td>Contact</td>
<td>WCT</td>
<td>sec</td>
<td>0.22</td>
<td>0.05</td>
<td>-0.033</td>
<td>0.041</td>
<td>0.155</td>
</tr>
<tr>
<td></td>
<td>Foot Depth</td>
<td>m</td>
<td>-0.33</td>
<td>0.07</td>
<td>-0.660 **</td>
<td>0.110</td>
<td>0.169</td>
</tr>
<tr>
<td></td>
<td>Tuck Index</td>
<td>%</td>
<td>60.35</td>
<td>11.19</td>
<td>0.300</td>
<td>-0.373</td>
<td>-0.377</td>
</tr>
<tr>
<td></td>
<td>Stretch Index</td>
<td>%</td>
<td>78.72</td>
<td>8.47</td>
<td>-0.278</td>
<td>-0.102</td>
<td>-0.094</td>
</tr>
<tr>
<td>Turn-out</td>
<td>3mTurn-outT</td>
<td>sec</td>
<td>0.59</td>
<td>0.09</td>
<td>0.532 *</td>
<td>-0.321</td>
<td>-0.671 **</td>
</tr>
<tr>
<td></td>
<td>15mTurn-outT</td>
<td>sec</td>
<td>7.72</td>
<td>0.36</td>
<td>0.795 **</td>
<td>-0.454</td>
<td>-0.461</td>
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<tr>
<td>Glide</td>
<td>GIV</td>
<td>m/sec</td>
<td>2.37</td>
<td>0.28</td>
<td>-0.270</td>
<td>0.317</td>
<td>0.500</td>
</tr>
<tr>
<td></td>
<td>GIAngle</td>
<td>deg</td>
<td>-2.56</td>
<td>3.91</td>
<td>0.611 *</td>
<td>-0.212</td>
<td>-0.257</td>
</tr>
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</table>

Notes: * p<0.05, ** p<0.01. The depth of the water showed with a negative value.

The 3mRTT was 3.02 ± 0.11 sec, and had significant correlations with 3mTurn-inT (r = 0.797 p < 0.01), with ApV (r = -0.576 p < 0.05), and with RoV (r = -0.579 p < 0.05). The 3mRTD was 4.87 ± 0.27 m and was significantly associated with the major axis (r = 0.757, p < 0.01), with the minor axis (r = 0.682, p < 0.01). The WCT was 0.22 ± 0.05 sec. It was shorter than that of previous studies (0.34 ± 0.05 sec, Puel...
et al. 2012 and 0.32 ± 0.04 sec, Lyttle et al. 1999). Because the change of the bubble attached to the foot was considered to be the first contact in the present study, it was thought that the WTC in this study was near to the Push-off time in previous studies (0.23 ± 0.05 sec, Puel et al. 2012 and 0.22 ± 0.05 sec, Lyttle et al. 1999). During the Contact phase, the RoD was 1.15 ± 0.12 m, and the Tuck Index was 60.35 ± 11.19%, and the Stretch index was 78.72 ± 8.47%.

The elliptic indices indicated significant correlations among each other (the inclination with the major axis = -0.580, p < 0.05, and with the minor axis = -0.578, p < 0.05; the major axis with the minor axis = 0.760, p < 0.01).

The inclination had significant correlations with the 15mTurn-outT (r = 0.795, p < 0.01), with the Foot Depth (r = -0.660, p < 0.01), with the GlAngle (r = 0.611, p < 0.05), with the Head Depth (r = 0.540, p < 0.05), and with the 3mTurn-outT (r = 0.532, p < 0.05). Moreover, the major axis showed significant correlations with the Head Depth (r = -0.766, p < 0.01). Furthermore, the minor axis were significantly correlated with the 3mTurn-inT (r = 0.569, p < 0.05), with the RoV (r = -0.625, p < 0.05), and with the 3mTurn-outT (r = -0.671, p < 0.01).

**Discussion**

Because the trajectory of the head during the rotation phase accorded with an elliptical model well, it was thought that those elliptic indices were proper to evaluate characteristics of the rotation in the tumble turn.

The 3mRTT was shorter than the result of general age group swimmers (2.5mRTT = 3.70 ± 0.47 sec, Blanksby 1996), and was slightly longer than the result of high level swimmers (3mRTT = 2.88 ± 0.10, and 2.62 ± 0.12, Puel et al. 2010, 2012). The turn performances of the subjects in the present study were lower than top swimmers and were higher than general youth swimmers. It considered that it was proper because those subjects were regional representatives. The 3mRTT was influenced by the swimming performance level of the subject. The RoD was shorter to the Head–wall distance at rotation in the previous study (1.20 ± 0.13 m, Puel et al. 2012). It was longer than general youth swimmers in the previous study (the Turn start distance = 0.62 ± 0.18 m, Blanksby 1996). The Tuck index was similar to the Lower limb extension index at the beginning of push-off in the previous studies (56.6 ± 17.2% of youth swimmers, Blanksby et al. 1996; 57 ± 8% of college students, Prins & Patz 2006; 62 ± 8% of elite swimmers, Puel et al. 2012). It was thought that the Tuck Index tends to increase with a competitive level. The Stretch index tended to be smaller than the upper body extension index at the beginning of push-off in the previous study (90 ± 6%, Puel et al. 2012). It seemed that increasing of the Stretch Index help to make a streamline early.

Because the inclination of the elliptic positive influenced the 15mTurn-outT, it was thought that the inclination should be shallower. As the inclination had the significant negative correlations with the major axis, also with the minor axis, a shallower inclination causes the rotation to start far from the wall and makes a larger ellipse. Some previous studies indicated that the swimmers with the fastest turns initiated their rotation farther from the wall (Puel et al. 2012; Blanksby et al. 1996). It was not only beginning rotation farther from the wall, but also keeping speed toward the wall. Costill et al. (1992) gave a suggestion that a small dolphin kick during the final arm stroke to assist in pushing the hips up.

The 3mRTD was about the same with the previous study (the Total distance covered from 3m in to 3m out = 4.88 ± 0.31 m, Puel et al. 2012). The best tumble turn was characterised by a long the RoD, the slower horizontal speed at the force peak, and reduced the 3mRTD (Puel et al. 2012). In the present study, the 3mRTD had a significant positive correlation with the major and minor axis correlation. A large elliptic trajectory caused the deeper head depth. Therefore, it was thought that a large elliptic trajectory was the factor of the 3mRTD extension. It was suggested that a flattened ellipse (shorter minor axis) was desirable, because the correlation of the minor axis with the 3mTurn-inT was positive, and with the RoV was negative.
**Conclusion**

In conclusion, the purpose of this study was to evaluate of the tumble turn in swimming based on an elliptical model. Subjects were 15 junior male regional representative swimmers that asked to perform 15 m round trip crawl stroke, including a tumble turn as fast as possible. Results on evaluation of the elliptic model for a tumble turn in swimming were identified as follows: (1) The trajectory of the head during the rotation phase accorded with an elliptical model well; (2) The inclination of the ellipse positive influenced to the 15m turn-out time; (3) The correlation of the minor axis with the 3m turn-in time was positive, and with the horizontal speed during head rotation was negative. It was suggested that the elliptic trajectory of the head during the rotation phase was shallower inclination and flattened of the ellipse had advantageous to turn performance.

**Acknowledgments**

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**References**


A method to calculate the vertical force produced during the eggbeater kick

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Keywords: biomechanics, water polo, eggbeater kick

Introduction

The eggbeater kick is a technique used in water polo and synchronised swimming. Assessing eggbeater kick performance or comparing different performers has been done by determining the height achieved during the kick in the vertical position (Sanders 1999; Homma & Homma 2006; Klauck 2006). Such methods are limited to the position of one anatomic marker (i.e. vertex, trochanter) and do not account for the subject’s mass or buoyancy factors. The purpose of this study was to develop a method to determine the vertical force produced during the eggbeater kick.

Methods

One water polo player (87.71 Kg; 1.92 m) was recorded by four underwater video cameras and one above water camera while executing the eggbeater kick in the vertical position. The subject was instructed to maintain as high a position as possible for as long as possible. Anthropometric data were collected using the ‘eZone’ method (Jensen 1978; Deffeyes & Sanders 2005). Three dimensional coordinates for the lower limbs comprising the feet, shanks and thighs (FST) and two dimensional coordinates of the above water top of the sternum marker representing the head, arms and trunk (HAT) were manually digitised from the video recordings. To determine the weight and buoyancy factors the subject was weighed and digitised at different water levels from the bottom of the sternum to the neck while suspended in the vertical position using a swimming pool hoist and a harness (Fig. 1). A subject-specific second degree regression equation (1) was established from the net weight-buoyancy force and height data to enable prediction of the weight-buoyancy force contribution to net vertical force given the height from the digitised video data as input.

\[(\text{Weight + Buoyancy}) = -0.0023ht^2 + 0.71ht + 17.76\]  

The vertical force produced during the cycle at any given time (t) was calculated using the formula:

\[V_{\text{Force}}(t) = (\text{Weight + Buoyancy})_t + (y_{\text{FST com}} \times \text{FST mass}) + (y_{\text{HAT}} \times \text{HAT mass})\]

where \((\text{Weight + Buoyancy})_t\) is calculated from the regression equation, \(y_{\text{FST com}}\) is the vertical acceleration of the FST system center of mass, and \(y_{\text{HAT}}\) is the vertical acceleration of the HAT system represented by the black tape marker. The FST center of mass is calculated by taking the moments about each axis for each lower body segment using the segments mass previously calculated. The acceleration for both systems was calculated using the central difference formula. Each cycle was normalised to 101 points (100%) and the mean was calculated for each point. The cycle starts at maximum extension of the right knee.
Results

Figure 2, 3 and 4 show the values of vertical force, $yF ST_{\text{com}}$ and $yH A T$ components during one representative cycle. The representative cycle results from calculating for each point the mean of the same time point of nine cycles.

Solid line represents the mean and dashed line the 95% confidence interval.

Figure 1 Camera view to determine the weight and buoyancy factors

Figure 2 Representative cycle of the vertical force produced
Solid line represents the mean and dashed line the 95% confidence interval.

**Figure 3** Representative cycle of the yFSTcom component acceleration

Solid line represents the mean and dashed line the 95% confidence interval.

**Figure 4** Representative cycle of the HAT component acceleration
Figure 5 shows that the maximum values of vertical force for this player were obtained during the transition phases of the feet between the highest and lowest points, corresponding to 30 – 40% and 85 – 95% of the time in the cycle. The minimum values were obtained approximately at the peaks, high and low, in each foot’s path, corresponding to 7 – 17% and 60 – 70% of the time in the cycle.

**Conclusion**

The present study suggests a method to obtain instantaneous net force during the eggbeater kick. Anthropometrics of individual subjects are taken into account and it offers the possibility to establish a relationship between the force produced and other variables calculated during the cycle such as position of the feet.

**References**


A new approach for identifying phases of the breaststroke wave kick and calculation of feet slip using 3D automatic motion tracking

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Keywords: swimming, breaststroke, kick, phases, biomechanics, 3D automatic motion tracking

Abstract
This study proposes a new method for identifying the different phases of the leg kick in the modern breaststroke technique. Previous analysis models assume that all breaststroke kicks finish with feet actively coming together during the insweep followed by a ‘flat glide’ and active knee bend to start the recovery. Using the previous models for the swimmers tested the phases could not be accurately separated due to the different wave amplitudes in their technique influencing their insweep and knee bend timing during recovery. Four phases of the breaststroke kick were therefore identified using 3D automatic motion tracking: 1) propulsion, from the smallest knee angle during recovery of the legs until the first peak in knee angle during propulsion, 2) insweep/wave motion/glide, from end of phase 1 until second peak in knee angle, 3) first part of the recovery, from end of phase 2 until 90 degree knee angle and 4) second part of recovery, from end of phase 3 until legs reach position 1. The method uses distinct positions of the 3D markers, their trajectory and peak angles to give a better understanding of the phases in the modern breaststroke technique as well as accounting for different styles of breaststroke technique.

Introduction
The Fédération Internationale de Natation (FINA) rule change on February 15th 1987 allowed the swimmers to break the water surface during arm recovery and dive below the water surface with their head during a breaststroke cycle (Colman et al. 1998). This started the evolution of the wave/dolphin style breaststroke technique, used today by almost every competitive breaststroker. Dividing the arm stroke and leg kick into phases has offered researchers to study the motor patterns and interlimb coordination during the different swimming strokes. The first studies in swimming looking at motor patterns came from Vaday et al. (1971) in front crawl and Nemessuri et al. (1971) in breaststroke. Since then, several authors have studied motor patterns and interlimb coordination in breaststroke (e.g. Chollet et al. 1999; Chollet et al. 2004; Costill et al. 1992; Leblanc et al. 2009; Sanders 1996; Seifert et al. 2005; Seifert et al. 2006; Seifert et al. 2009; Seifert et al. 2010; Seifert et al. 2011; Soares et al. 1999). These authors analyzed the spatial-temporal relationships between the key points defining the start and the end of each arm and leg stroke phase. Four distinct breaststroke techniques have been identified: vertical, flat, undulating and undulating with arm recovery over the water, which lead to difficulties of finding an ideal mode for arm and leg coordination (Maglischo 1993; Persyn et al. 1992; Tourny et al. 1992; Vilas-Boas et al. 1994; Vilas-Boas 1996). A recent method to analyze breaststroke was developed by Chollet et al. (2004), who identified five phases for both arms and legs and measured the time gaps between the phases using a speedometer-video. These five phases of the breaststroke leg kick are identified as: leg propulsion, leg insweep, leg glide, first part of the recovery until a thigh/leg angle of 90° and second part of the recovery. Chollet et al. (2004) and Seifert et al. (2005) applied this method to analyze the flat style breaststroke and proposed a new index for the arm- and leg coordination in elite and recreational swimmers. Today, there is no specific index for the wave breaststroke or one that encounters all the different breaststroke styles. The purpose of this study was to investigate a new way of identifying and measuring the phases during the breaststroke wave kick and the slip of the foot allowing for a more careful study of technical aspects in each phase using 3D automatic motion tracking.
**Methods**

**Participants**

Three international top level swimmers (two male World champions’ and one female Olympic medalist) (27.3 ± 1.7 years; 188 ± 2.83 cm; 86.55± 0.78 kg) and 1 female (28.3 years; 168 cm; 73.3 kg) participated in this study. All participants signed informed consent approved by the Norwegian national ethics committee and volunteered to participate in this study.

**Motion capture system**

A 3D underwater motion capture system (Qualisys, Gothenburg, Sweden) consisting of Oqus 3 and 4 cameras were installed in the pool to record underwater movements for kinematic analysis. The cameras used a high-powered led light with a cyan visible strobe (wavelength of 505nm). To counter the fact that water absorbs light at a much higher degree than air, the underwater cameras were equipped with a very powerful strobe consisting of 12 high power LEDs. The powerful LED solution provided good illumination for 12.5m in clear water and facilitated measurements even with a certain degree of particles in the water. Each LED was also equipped with a lens which focuses the light to approximately a 40 degree wide beam. By angling the LEDs individually an even light pattern was produced over the entire field-of-view (FOV) of the cameras. All cameras were placed inside a waterproof case IP68 and IP69K (Qualisys, Gothenburg, Sweden). Each camera had an active filtering hardware, which greatly reduced unwanted reflections from bubbles and other objects under water. Each camera was also masked for sunlight reflections. The specialised underwater cameras were connected to a power supply, synchronised, and attached to a PC using an Ethernet connection. Qualisys Track manager 2.6 (Qualisys, Gothenburg, Sweden) was used for running the camera setup and capture. The cameras were operating at 100 Hz capturing special retro reflective markers on the swimmers body. Camera set-up consisted of 10 underwater cameras, 5 on each side of the pool, 6 were mounted just below the water surface and 4 were standing on tripods under water (Fig. 1).

![Figure 1 Underwater cameras](image)

**Markers**

The retro reflective material used on normal land markers completely loses reflectivity under water. Therefore, spherical markers of special material suitable for underwater usage were produced by Qualisys (Gothenburg, Sweden). The markers were passive spheres and half spheres with a diameter of 19 mm and where all equipped with a thread for fastening and neutral buoyancy (Fig. 2). They were placed on the swimmers cresta ilíaca, trochanter major, distal part of vastus lateralis (glued to the swimmers suit), lateral femoral condyle, peroneus longus, the most posterior part of the calcaneus, medial and lateral malleolus and metatarsals 1 and 5.

**Calibration**

Calibration of the 3D motion capture system was performed with an L-frame and a moving wand method (Nedergaard et al. 2013) with two markers fixed with inter-point distance of 749.5 mm following the recommendations of the manufacturer (Qualisys AB 2011). The wand was manually moved through the calibration volume following the path of the swimmers for 300 sec to cover as
many points as possible, at least 800-1000 per camera. During this process the ‘extended calibration’
option was active because all cameras were not able to view the L-frame, which was placed in the
middle of the volume on the bottom of the pool. The standard deviation of the wand markers
distance during calibration was 1.6 mm. The cameras covered a volume of approximately 37.5 m³, 10
m (x) x 1.5 m (y) x 2.5 m (z) and is presented in Fig. 3.

Figure 2 3D marker  Figure 3 The calibrated volume under water

Testing and kinematical analysis

After a personalised warm-up with the equipment, consisting of 15 min of low- to moderate-intensity
aerobic swimming with elements of kicking and drills, the swimmers swam all exercises in the same
order. Borg’s Rate of Perceived Exertion (RPE) was used to verify the swimmers effort (Borg 1998).
The swimmers performed five trials of 20 m normal breaststroke at 60-70-80-90-100% of maximal
effort and the 100% trial were analyzed. The second and third last stroke cycles were selected to
avoid influence of approaching the wall on the last stroke. The leg kick was divided into 4 phases: 1)
propulsion, from the smallest knee angle during recovery of the legs until the first peak in knee angle
during propulsion, 2) insweep/wave motion/glide from end of phase 1 until second peak in knee
angle, 3) first part of the recovery, from end of phase 2 until a 90 degree knee angle and 4) second
part of recovery, from end of phase 3 until legs are back in position 1. The slip of the feet was
calculated from the starting point of phase 1 until the x-direction of the ankle marker went from
moving backwards to moving forward. An example of a 3D model of the leg kick with automatic
tracking is presented in Fig. 4.

(a) beginning of phase 1, (b) beginning of phase 2, (c) beginning of phase 3, (d) beginning of phase 4, (e) end of phase 4. Color
coding of the markers on the bone structure from left to right: ⚫ calcaneus and metatarsals, ⚫ lateral femoral condyle,
⚫ trochanter major and ⚫ cresta ilaca.

Figure 4 Underwater breaststroke kick with 3D automatic tracking

Results

The four phases of the breaststroke kick during 100% maximal effort and the slip of the feet are
shown in Table 1. Swimmer #3 with the most distinct wave breaststroke also showed a much larger
knee angle in the beginning and at the end of phase 1 as well as a smaller knee angle in phase 2 and 3.
The slip was similar across the subjects, ranging from 300-320 mm.
Table 1

Times (sec), % of time, knee angles (°) and slips (mm) are shown for the five phases of the breaststroke kick coordination

<table>
<thead>
<tr>
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<th>P.1</th>
<th>.24</th>
<th>.50</th>
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<tr>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

#1, 2, 3 refers to the subjects. P.1, 2, 3, 4 refers to the four different phases of the breaststroke kick.

Discussion

This study identified a new model for analyzing the different phases of the breaststroke kick in order to account for the different technique styles used by competitive swimmers. In the past, several models to investigate motor patterns, interlimb coordination and intra-cyclic velocity variations in breaststroke have been presented. These models have a varied number of phases for the arm pull and leg kick. Colman et al. (1992; 1998) digitised 12 images with stick figures to divide the stroke into 8 phases. The newest analysis method from Chollet et al. (2004) divided both the arm pull and leg kick into five separate phases in order to investigate arm-leg coordination in flat breaststroke. The same model has later been used by Leblanc et al. (2005) and Seifert et al. (2005) to evaluate recreational and elite swimmers with the flat breaststroke technique. The challenge with this method for analyzing the breaststroke kick in terms of phases is the assumption that all breaststroke kicks finish with the feet actively coming together during the insweep followed by a ‘flat glide’ and active knee bend to start the recovery. When applying this method to the swimmers tested in this study, the phases could not be accurately separated due to different wave amplitudes in their technique, influencing both the insweep and knee bend during recovery. Instead of a more traditional up, out, in and glide kick type, these swimmers performed a much more rounded kick which did not always end with the feet being pushed actively together during the insweep. Rather kicking their legs into a wave motion/up-kick was the most observed pattern. The image from Colman et al. (1998) (legs parallel to each other and in line with the hips) would provide a more distinct parameter that could be used for analyses across different technique styles. Chollet et al. (2004) described the first part of the recovery starting with knee flexion and forward movement of the feet. For the subjects tested in this study, knee flexion during the glide as well as forward movement of the feet as a consequence was observed. However, there was still no sign of an active recovery of the legs.

Conclusion

This study proposes a new method for identifying the different phases of the leg kick in the modern breaststroke technique in order to compare swimmers with different techniques. To give a better understanding of the phases, this new method uses distinct positions of markers, their trajectory and peak angles to identify the phases of the modern leg kick.

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Muscle activation and kinematic differences between breaststroke swimming and technique/drill exercises: A case study of a world champion breaststroker

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Keywords: breaststroke, swimming, surface electromyography, drill exercise, biomechanics phases, 3D motion capture

Abstract
Breaststroke swimmers perform technique and drill exercises in their daily training in order to improve their competitive breaststroke swimming. This has previously been looked upon in different kinematic studies, but no study combined this with surface electromyography. One male world champion breaststroker swam regular breaststroke at 60% and 100% of maximal effort and performed one common technique exercise, 2 breaststroke kicks to 1 breaststroke pull at 100% of maximal effort. Biceps femoris, rectus femoris, gastrocnemius medialis and tibialis anterior were analyzed for four different phases of the breaststroke kick using surface electromyography (sEMG). 3D automatic motion tracking was used to identify the four phases of the breaststroke kick. Integrated EMG (iEMG) for the four phases showed that swimming at 60% and 100% had the highest activation in 15 of the 16 conditions (across the 4 phases and the 4 muscles) while the 1st kick in 2 kicks to 1 breaststroke pull showed a peak for gastrocnemius medialis in phase 4. The lowest iEMG activation occurred during 2 kicks to 1 breaststroke pull in 13 conditions and 0 times in swimming at 60% effort. The study showed different muscle activation patterns between regular breaststroke swimming and a common technique/drill exercise.

Introduction
Kinesiological electromyography (EMG) can be used to identify the coordination, synchronisation and intensity of muscle activation. Recording EMG while swimming can give an expression of the dynamic involvement and the relative contribution of specific muscles in the propulsion of the body through the water (Clarys 1985) The first recordings of underwater EMG signals on humans during swimming were done by Ikai et al. (1964). Lewillie (1967; 1968) introduced techniques using telemetry EMG measurements. This was later improved by Piette et al. (1979) and Clarys et al. (1983). These early studies provided new insight into an important area of swimming technique, but also had their limitations and challenges. Since then, the use of EMG in swimming and water exercises has become increasingly popular in order to monitor and objectivise muscle activity. In swimming, there are still quite few studies on muscle activation available (about 80 articles). The vast majority of these articles were conducted prior to the 1980s and mostly in freestyle swimming. Only limited amounts of research have been carried out in other swimming styles (breast- and backstroke, butterfly and dolphin kicking). Today, only about 15 articles have been published measuring muscle activity using EMG and kinematics in breaststroke. Quite a few of these studies were also conducted prior to the Fédération Internationale de Natation (FINA) rule change in 1987 which introduced the new wave/dolphin style breaststroke. Technique and mechanics of breaststroke swimming have gone through a tremendous change over the past 20 years from what was called the ‘flat breaststroke’ used by every swimmer, to the modern technique of wave breaststroke. Today this new wave technique is used by almost every competitive breaststroker.

Fontana et al. (2009) advocated that motor learning textbooks provide specific recommendations for the use of ‘whole’ and ‘part’ practice during motor skill acquisition. Part practice involves breaking a skill into smaller units, whereas whole practice involves practicing a motor skill in its entirety. While part practice may simplify skill rehearsal, it may also change the biomechanics, timing of the task and
muscular activation. Comparing muscle activation with the use of EMG was studied in swimming with regards to weight and dry land training versus swimming the stroke and with fully tethered swimming. Schleihauf (1983) observed ‘nonspecific’ EMG records when dry land EMG records were compared to ‘wet’ EMG records. Olbrecht et al. (1983) found that specific training cannot be accomplished with dry land devices because of mechanical and environmental differences. Bollens et al. (1988) found that fully tethered freestyle swimming is similar to normal free swimming. In breaststroke, Daniel et al. (1999) found muscular coordination to be similar between the arm pull in free breaststroke swimming, fully tethered breaststroke swimming and arm pulling using different land training devices in four typical propulsive muscles. They also found that speed parameters could not be imitated. In the literature, there is no known published research comparing muscular activity of different technique/drill (part practice) exercises to the muscular activity during breaststroke swimming. The closest research today is Conceição et al. (2010) investigating the standard average muscle activation with and without the use of a snorkel while swimming breaststroke technique. In order to identify the specificity of an exercise it is important to know whether the motor unit action potential (MUAP) is the same, similar or different from the normal movement. The aim of this study was therefore to investigate the relationship between muscle activation and kinematics in four different leg muscles during normal breaststroke swimming at different 60 and 100% of maximal effort and during a common technique/drill exercise including 2 leg kicks to 1 arm pull at 100% of maximal effort.

Methods
Participants
One world champion male breaststroker (26.1 year; 190 cm; 87.1 kg) volunteered to participate in the study. Informed consent approved by the national ethics committee was signed.

Surface electromyography
Muscle activation was recorded with surface EMG from four leg muscles on the right side of the body, m. rectus femoris, m. biceps femoris, m. tibialis anterior and m. gastrocnemius medialis. To minimise (electrical) resistance of the skin, electrode sites were shaved with disposable razors and cleaned with alcohol. Disposable, self-adhesive, waterproof pre-gelled Ag-Ag:Cl electrodes with contact surface diameter of 10 mm and diameter of 57 mm with snap connector of 3.9 mm diameter (Plux Ltda, Lisbon, Portugal) were positioned in line with the direction of the muscle fibers. Anatomical references for the electrode placement were determined by the recommendations of the SENIAM project for the respective muscles tested (Hermens et al. 1999). A ground electrode was placed in the middle of the forehead. The electrodes were covered with insulating tape around the outside perimeter for protection of the water flow and resistance during swimming. The electrodes were connected to waterproof active sensors for EMG (Plux Ltda, Lisbon, Portugal) with a band pass filter of 25-500 Hz (-6 dB), input impedance >100 MOhm, CMRR 110 dB and with a gain of 1000. The active sensors were connected to the bioPlux Research (Plux Ltda, Lisbon, Portugal) using wires running inside a waterproof pouch with 8 analogue channels (12 bit) and sampled at a rate of 1000 Hz. A more detailed explanation of the EMG set-up and recording can be found in Olstad et al. (2011).

Data analysis of surface electromyography
MATLAB R2012b software (MathWorks Inc., Natick, MA, USA) was used for processing the EMG signal. The raw EMG signals were filtered through a fourth-order Butterworth band-pass filter (bandwidth 8-500 Hz), rectified and averaged in order to obtain the full wave signals. The signals were partitioned in 40 ms windows throughout the measurement file to find the maximal iEMG for each muscle. To eliminate the effect of phase duration the integration of the EMG signal was calculated per unit of time for the duration of each of the four phases (iEMG/T). To normalise the results the average iEMG over the four phases were then expressed as iEMG/T (%). The maximum and minimum 40 ms window throughout the stroke cycle were also calculated and expressed as % into the stroke cycle were it occurred. A more detailed overview of the data processing can be found in Lauer et al. (2013).
**Motion capture system**

A 3D underwater motion capture system from Qualisys (Qualisys, Gothenburg, Sweden) consisting of Oqus 3 and 4 cameras were installed in the pool to record underwater movements for kinematic analysis. The software for running the camera setup and capture was Qualisys Track manager 2.6 (Qualisys, Gothenburg, Sweden). The cameras covered a volume of approximately 37.5m³, 10m (x) x 1.5m (y) x 2.5m (z). A detailed description of the system and set-up can be found in Olstad et al. (in press).

**Synchronisation of the equipment**

The pool was equipped with 1 digital underwater camera for synchronisation of the EMG signals with the 3D kinematics. A Sony HDR-CX550VE Camcorder, AVCHD, (Sony INC, Tokyo, Japan) was placed inside a Sony underwater housing SPK-CXA, (Sony INC, Tokyo, Japan). The camera was fixed at a depth of 0.60 m at the frontal side of the pool to record the underwater blink from the EMG synchronisation light.

**Testing and kinematical analysis**

After a personalised warm-up with the equipment that consisted of 15 min of low- to moderate-intensity aerobic swimming with elements of kicking and drills, the swimmer performed five trials of 20 m normal breaststroke at 60-70-80-90-100% of maximal effort and a common technique/drill exercise at 100% of maximum effort. The exercise was 2 breaststroke kicks to 1 breaststroke pull and performed as: one regular breaststroke cycle, followed by maintaining a streamlined position with the arms and performing the second kick. The Borg scale RPE (1998) was used to verify the swimmers effort level and the 60% and 100% swimming trials were analyzed together with the technique/drill exercise. The four phases of the breaststroke leg kick were analyzed: 1) propulsion, from the smallest knee angle during recovery of the legs until the first peak in knee angle during propulsion, 2) insweep/wave motion/glide, from end of phase 1 until second peak in knee angle, 3) first part of the recovery, from end of phase 2 until 90 degree knee angle and 4) second part of recovery, from end of phase 3 until legs are back in position 1. The second and third last stroke cycles were selected to avoid influence of the wall on the last stroke. The phases of each breaststroke cycle and kinematic set-up were defined in Olstad et al. (in press).

**Results**

The normalised iEMG for the four phases showed that swimming at 60% and 100% had the highest activation in 15 of the 16 conditions (across the 4 phases and the 4 muscles) while the 1st kick in 2 kicks to 1 breaststroke pull showed a peak for gastrocnemius medialis in phase 4. The lowest iEMG activation occurred during 2 kicks to 1 breaststroke pull in 13 conditions and 0 times in swimming at 60% effort. The highest normalised iEMG activation occurred in phase 1 of swimming at 60% of maximal effort with 91.7% for rectus femoris and 87.3% for gastrocnemius medialis. The highest activation was found in phase 1 and 4 for all muscles. The normalised iEMG values for the selected phases are displayed in Table 1.
Table 1  The percentage of normalised integrated electromyography for time in phases 1, 2, 3 and 4 of the breaststroke kick

<table>
<thead>
<tr>
<th>Phase</th>
<th>Exercise</th>
<th>Gastrocnemius medialis</th>
<th>Tibialis anterior</th>
<th>Biceps femoris</th>
<th>Rectus femoris</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Phase 1</td>
<td>Swim 60%</td>
<td>87.3%</td>
<td>3.6%</td>
<td>34.6%</td>
<td>91.7%</td>
</tr>
<tr>
<td></td>
<td>Swim 100%</td>
<td>79.4%</td>
<td>2.3%</td>
<td>44.3%</td>
<td>78.3%</td>
</tr>
<tr>
<td></td>
<td>2kicks 1pull 100%</td>
<td>56.4%</td>
<td>1.2%</td>
<td>25.4%</td>
<td>43.4%</td>
</tr>
<tr>
<td></td>
<td>kick1</td>
<td>71.8%</td>
<td>0.7%</td>
<td>13.9%</td>
<td>33.5%</td>
</tr>
<tr>
<td></td>
<td>2kicks 1pull 100%</td>
<td>kick2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase 2</td>
<td>Swim 60%</td>
<td>39.6%</td>
<td>0.2%</td>
<td>7.0%</td>
<td>22.2%</td>
</tr>
<tr>
<td></td>
<td>Swim 100%</td>
<td>42.0%</td>
<td>0.5%</td>
<td>9.1%</td>
<td>24.4%</td>
</tr>
<tr>
<td></td>
<td>2kicks 1pull 100%</td>
<td>kick1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>kick1</td>
<td>27.8%</td>
<td>0.3%</td>
<td>9.0%</td>
<td>8.5%</td>
</tr>
<tr>
<td></td>
<td>2kicks 1pull 100%</td>
<td>kick2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase 3</td>
<td>Swim 60%</td>
<td>22.2%</td>
<td>1.9%</td>
<td>12.7%</td>
<td>15.6%</td>
</tr>
<tr>
<td></td>
<td>Swim 100%</td>
<td>21.4%</td>
<td>1.3%</td>
<td>16.2%</td>
<td>23.0%</td>
</tr>
<tr>
<td></td>
<td>2kicks 1pull 100%</td>
<td>kick1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>kick1</td>
<td>21.8%</td>
<td>0.9%</td>
<td>15.2%</td>
<td>15.4%</td>
</tr>
<tr>
<td></td>
<td>2kicks 1pull 100%</td>
<td>kick2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase 4</td>
<td>Swim 60%</td>
<td>59.0%</td>
<td>5.1%</td>
<td>48.5%</td>
<td>69.5%</td>
</tr>
<tr>
<td></td>
<td>Swim 100%</td>
<td>49.1%</td>
<td>2.4%</td>
<td>37.1%</td>
<td>59.8%</td>
</tr>
<tr>
<td></td>
<td>2kicks 1pull 100%</td>
<td>kick1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>kick1</td>
<td>59.2%</td>
<td>1.2%</td>
<td>22.4%</td>
<td>41.7%</td>
</tr>
<tr>
<td></td>
<td>2kicks 1pull 100%</td>
<td>kick2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Phase 1: propulsion, from the smallest knee angle during recovery of the legs until the first peak in knee angle during propulsion. Phase 2: insweep/wave motion/glide, from end of phase 1 until second peak in knee angle. Phase 3: first part of the recovery, from end of phase 2 until 90 degree knee angle. Phase 4: second part of recovery, from end of phase 3 until legs are back in position 1.

For all exercises the maximum iEMG occurred in phase 1 (propulsion) of the leg kick while the minimum iEMG occurred in either phase 2 (insweep/wave motion/glide) or phase 3 (first part of the leg recovery), except for gastrocnemius medialis who showed the least activation in phase 3. An overview of where the maximum and minimum iEMG occurs within a stroke cycle is displayed in Table 2.

Table 2  Time normalised position (100% = stroke cycle time) of the maximum and minimum integrated electromyography

<table>
<thead>
<tr>
<th>Stroke cycle Time (s)</th>
<th>Gastrocnemius medialis</th>
<th>Tibialis anterior</th>
<th>Biceps femoris</th>
<th>Rectus femoris</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>1.71</td>
<td>8.3% (P1)</td>
<td>0.1% (P1)</td>
<td>0.1% (P1)</td>
</tr>
<tr>
<td>Swim 60%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swim 100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2kicks 1pull 100%</td>
<td>1.69</td>
<td>11.4% (P1)</td>
<td>0.1% (P1)</td>
<td>0.1% (P1)</td>
</tr>
<tr>
<td>kick1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2kicks 1pull 100%</td>
<td>1.51</td>
<td>12.3% (P1)</td>
<td>3.1% (P1)</td>
<td>1.7% (P1)</td>
</tr>
<tr>
<td>kick2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>1.71</td>
<td>59.0% (P3)</td>
<td>44.7% (P2)</td>
<td>50.4% (P2)</td>
</tr>
<tr>
<td>Swim 60%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swim 100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2kicks 1pull 100%</td>
<td>1.69</td>
<td>67.9% (P3)</td>
<td>54.3% (P2)</td>
<td>57.5% (P2)</td>
</tr>
<tr>
<td>kick1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2kicks 1pull 100%</td>
<td>1.51</td>
<td>74.1% (P3)</td>
<td>69.8% (P3)</td>
<td>60.8% (P3)</td>
</tr>
</tbody>
</table>

P1: propulsion, from the smallest knee angle during recovery of the legs until the first peak in knee angle during propulsion. P2: insweep/wave motion/glide, from end of phase 1 until second peak in knee angle. P3: first part of the recovery, from end of phase 2 until 90 degree knee angle.

Discussion

The main finding in this study was that maximal iEMG appears to be different when swimming normal breaststroke at 60% and 100% of maximal effort compared to 2 kicks and 1 pull at 100% of maximal effort. Except for gastrocnemius medialis in phase 4 of the 2 kicks to 1 pull exercise swimming normal breaststroke at 60% and 100% effort showed the highest muscle activation. Also interesting in this case study is the decrease in participation from the rectus femoris, gastrocnemius medialis and tibialis
anterior from 60% effort at normal swimming to 100% effort at normal swimming in phase 1 and 4, while there is an increase in participation from biceps femoris in phase 1. Comparing the 100% effort at normal swimming with the 2 kicks to 1 pull exercise, the normal swimming showed higher muscle participation in 14 out of 16 conditions. This could be related to the position of the swimmer during the second kick in this exercise. The first kick is performed with a normal breaststroke cycle, while the second kick is performed with the upper body in a streamlined position and this might cause less dolphin/wave motion through the exercise. The second kick in this exercise also shows in most cases that maximum and minimum activation occurs later into the kick cycle than for the other exercises. On the contra dictionary gastrocnemius medialis showed lower participation while swimming at 100% effort in phase 3 and 4 compared with the other exercises.

Fontana et al. (2009) believed that part practice may simplify skill rehearsal, but it may also change the biomechanics, timing of the task and muscular activation. This study was conducted on a world champion breaststroker and it is the first step to investigate muscular activation in terms of normal breaststroke swimming and the technique exercises athletes do ‘every day’ in order to improve their performance. Fontana et al. (2009) suggested that for beginners learning the different movements, part practice could be valuable, but for world-class athletes the different exercises should be carefully selected since some of them might alter their already established and good working muscular recruitment and participation pattern.

Conclusion
A case study of a world champion breaststroker showed differences in muscle activation patterns between swimming at different effort levels and a common technique/drill exercise. From these data it may be considered that world-class athletes should select their different technique/drill exercises carefully so it does not alter their already established and good muscular recruitment and participation pattern. With regards to velocity and different technique and drill exercises more research and subjects are needed in order to fully understand what impact these differences have on the normal breaststroke technique and what considerations should be made in order to use certain common technique/drill exercises in order to improve the competitive technique.

References
Buoyant (leg-sinking) torque in able-bodied swimmers and swimmers with impaired leg function

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Keywords: buoyancy, torque, disability, floating

Introduction

A swimmer’s ability to float statically in a horizontal position is determined largely by the turning effect resulting from their body weight and buoyancy forces. This is termed the buoyant torque. As a body’s weight acts through its centre of mass (CoM) and the buoyancy force acts through its centre of buoyancy (CoB), the distance between these two centres will determine the static floating position of an individual (Gagnon & Montpetit 1981; McLean & Hinrichs 1998). In static floating, the CoB is generally closer to the head than the CoM. Consequently, the buoyant torque acts to sink the legs. Due to sex differences in body mass distribution, males generally experience a greater buoyant torque than females, resulting in a greater tendency for their legs to sink (Gagnon & Montpetit 1981; McLean and Hinrichs 1998).

Lung volume and arm position both influence buoyant torque (McLean & Hinrichs 2000). An increase in lung volume, by breathing in, increases the volume of the upper body without increasing its mass. This moves the CoB cranially with little or no effect on the CoM position. Consequently, the moment-arm of the buoyancy force increases thus increasing the buoyant torque. When one or both arms are extended overhead, the CoB and CoM both shift cranially, but the movement of the CoM is greater. This brings the weight and buoyancy forces closer together thus reducing the buoyant torque.

Drag is an important determinant of swimming performance. One of the key factors influencing drag is the projected frontal area of the swimmer which, in turn, is affected by the horizontal alignment of


the body in the water (Kjendlie, Stallman & Stray-Gundersen 2004). Para-swimmers who are unable to kick, due to impaired leg function, may be disadvantaged over those who compete in the same class but who are able to kick. Not only are they unable to use a leg-kick to help maintain horizontal alignment, but their body mass distribution, due to atrophied lower extremities, may differ from that of non-impaired swimmers and so, consequently, may the buoyant (leg-sinking) torque they experience. This study’s aim was to establish whether the buoyant torque differs between swimmers with impaired leg function and able bodied swimmers.

Methods

Participants: Testing was completed on six swimmers with impaired leg function (two male, four female), seven male able-bodied swimmers and seven female able-bodied swimmers. The impaired leg function group were international level competitors; the able-bodied groups were well-trained members of a university swim team. Ethical approval for the study was obtained from the Faculty Ethics Committee and written informed consent was obtained from each participant. All testing sessions were completed between 7-9 am in an attempt to control for alterations in supine height due to the time of day.

Measurement System: To determine the position of each participant’s centre of mass (CoM) and centre of buoyancy (CoB), a measurement system, based on that described by Gagnon and Montpetit (1981), was developed. This consisted of a rigid polythene spine board reinforced by aluminium square tube struts. The board was horizontal and free to pivot on a support frame located at one end. The other end was supported by a cable suspended from a load cell (Tedea-Huntleigh S type, model 616). Voltage output from the load cell was sampled at 100 Hz using a 12-bit analogue-digital converter (Picoscope, ADC42). An amplifier provided force ranges of 0-800 N and 0-200 N for above and below water measurements, respectively.

Test Protocol: Participants lay on the board in a supine position. Their feet were positioned in plantegrade with the soles pressed against a footplate. Velcro straps were fastened around the knees and waist to ensure that the participants remained in the same position throughout the testing session and to prevent the participants from floating during the underwater stage of the testing. Prior to taking force measurements, participants lay on the board for ten minutes in order to allow body fluids to settle.

The participants were tested in three standardised body positions: 1) both arms by the side of the body, 2) one arm fully extended above the head, the other at the side of the body, 3) both arms fully extended above the head. In each body position, measurements were taken in two breathing conditions. Participants were either instructed to take a full breath in (condition 1) or a full breath out (condition 2), without forcing any air in or out. These breathing conditions were used as research has suggested that swimmers use a lung volume of 50-75% of vital capacity (Dicker et al. 1980) and do not use maximal inspiration or expiration. During the underwater testing stage, the participants were fully submerged and so were required to breathe through a snorkel and wear goggles.
Force measurements were taken of the board alone above water and then with the participant on the board, in the three body positions. A minimum of two trials were performed for each position. The participant and board were then lowered into the water such that the board was again horizontal and free to pivot on the support frame (Figure 2). A 5 kg mass was added to both ends of the board to prevent the board and participant from floating. In each of the three body positions, the participant breathed in, held this for ten seconds and then breathed out and held this for ten seconds. This allowed both breathing conditions to be tested under identical body positions. When all the below water force measurements of the board plus participant had been made, the below water force measurement of the board alone was made.

The final step was to determine the buoyancy force of the participant by underwater weighing. The board was suspended from the load cell by four cables attached at the corners of the board. The participant, strapped to the board in a supine position, repeated the two breathing conditions used in the earlier underwater stage. Measurements were repeated three times and the mean value calculated for both conditions. The buoyancy force of the board alone was then determined.

**Calculation Procedure**: The method used to determine the CoM and CoB locations was based upon the Principle of Moments. For a rigid body in a state of equilibrium the sum of the anticlockwise moments about any point equals the sum of the clockwise moments about the same point. By taking moments about the pivot in the above water configuration (Figure 1), the location of the CoM was calculated as follows:

$$X_{\text{CoM}} = \frac{[R_2 - R_1] \cdot L}{W_P}$$  \hspace{1cm} (1)

Where:
- $X_{\text{CoM}}$ is the horizontal distance between the board pivot and the participant’s CoM;
- $R_1$ is the suspension force in the cable from the board alone, above water;
- $R_2$ is the suspension force in the cable from the board + participant, above water;
- $L$ is the perpendicular distance between the pivot and the cable;
- $W_P$ is the weight of the participant.

Similarly, by taking moments about the pivot in the below water configuration (Figure 2), the location of the CoB was calculated as follows:

$$X_{\text{CoB}} = \frac{[(R_3 + R_2 - R_1 - R_4) \cdot L]}{B_P}$$  \hspace{1cm} (2)

Where:
- $X_{\text{CoB}}$ is the horizontal distance between the pivot and the participant’s CoB;
- $R_1$ is the suspension force in the cable from the board alone, below water;
- $R_2$ is the suspension force in the cable from the board + participant, below water;
- $B_P$ is the buoyancy force of the participant.

The buoyant torque was then calculated as the product of the CoM-CoB distance and the buoyancy force:

$$\text{Buoyant Torque} = (X_{\text{CoB}} - X_{\text{CoM}}) \cdot B_P$$  \hspace{1cm} (3)
**Results**

The CoM and CoB were located significantly closer to the head in the impaired leg function swimmers, when compared to the able-bodied swimmers, in all three body positions and both breathing conditions. The position of the two centres did not differ significantly between the able-bodied male and female groups (Table 1).

**Table 1**

<table>
<thead>
<tr>
<th>Group</th>
<th>Breath Condition</th>
<th>Arms by side</th>
<th>One arm extended</th>
<th>Both arms extended</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILF Group (n=6)</td>
<td>Inspiration</td>
<td>61.2 ± 2.7*</td>
<td>63.1 ± 2.1*</td>
<td>65.3 ± 2.2*</td>
</tr>
<tr>
<td></td>
<td>Expiration</td>
<td>60.7 ± 2.5*</td>
<td>62.8 ± 2.3*</td>
<td>64.9 ± 2.2*</td>
</tr>
<tr>
<td>AB Female (n=7)</td>
<td>Inspiration</td>
<td>58.1 ± 1.5</td>
<td>59.7 ± 1.4</td>
<td>61.1 ± 1.6</td>
</tr>
<tr>
<td></td>
<td>Expiration</td>
<td>57.6 ± 1.1</td>
<td>59.4 ± 1.4</td>
<td>60.9 ± 1.5</td>
</tr>
<tr>
<td>AB Male (n=7)</td>
<td>Inspiration</td>
<td>57.6 ± 2.1</td>
<td>59.2 ± 2.1</td>
<td>61.1 ± 2.3</td>
</tr>
<tr>
<td></td>
<td>Expiration</td>
<td>56.8 ± 2.1</td>
<td>58.9 ± 2.0</td>
<td>60.8 ± 2.4</td>
</tr>
</tbody>
</table>

Locations are shown for three body positions and two breathing conditions (inspired and expired). Values are expressed as a percentage of the participants’ supine height measured from their lateral malleolus. * indicates a difference (p<0.05) between the ILF group and both AB groups.

In all groups, the CoM and CoB moved cranially as one arm, then both arms were extended overhead. In all conditions, the CoB was located closer to the head than was the CoM. For all participants in all the body positions, an inspiration caused the CoB to move cranially. However, the effect of breathing condition on CoB location was not statistically significant for any of the groups.

All groups in all conditions experienced a positive torque that acted to rotate their legs downward (Table 2). The buoyant torque was significantly higher for all groups, in all three body positions, following inspiration, compared to following expiration. Arm position did not significantly alter the buoyant torque, but there was a clear trend in the data for the torque to decrease as one arm, then both arms were extended overhead. The mean buoyant torque for the able-bodied male group was significantly higher than those for the able-bodied female and impaired leg function groups, in all conditions. The four impaired leg function females had a lower mean buoyant torque, in all conditions, than the able-bodied female swimmers. The two impaired leg function male swimmers experienced buoyant torques comparable to those of the able-bodied male swimmers, in most conditions.
Table 2  Buoyant torque acting about the transverse axis of swimmers with impaired leg function (ILF) and able-bodied (AB) swimmers

<table>
<thead>
<tr>
<th>Group</th>
<th>Breath Condition</th>
<th>Arms by side</th>
<th>One arm extended</th>
<th>Both arms extended</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILF Female (n=4)</td>
<td>Inspiration</td>
<td>6.5 ± 2.0</td>
<td>6.0 ± 2.3</td>
<td>4.3 ± 1.4</td>
</tr>
<tr>
<td></td>
<td>Expiration</td>
<td>4.0 ± 2.4</td>
<td>4.9 ± 3.6</td>
<td>3.6 ± 1.8</td>
</tr>
<tr>
<td>ILF Male (n=2)</td>
<td>Inspiration</td>
<td>19.3 ± 6.1</td>
<td>15.5 ± 2.7</td>
<td>13.1 ± 3.8</td>
</tr>
<tr>
<td></td>
<td>Expiration</td>
<td>9.6 ± 0.70</td>
<td>7.8 ± 0.2</td>
<td>5.0 ± 0.2</td>
</tr>
<tr>
<td>ILF Group (n=6)</td>
<td>Inspiration</td>
<td>10.8 ± 7.3</td>
<td>9.2 ± 5.4</td>
<td>7.2 ± 5.0</td>
</tr>
<tr>
<td></td>
<td>Expiration</td>
<td>5.9 ± 3.4</td>
<td>5.9 ± 3.2</td>
<td>4.1 ± 1.6</td>
</tr>
<tr>
<td>AB Female (n=7)</td>
<td>Inspiration</td>
<td>11.2 ± 3.3</td>
<td>10.0 ± 3.1</td>
<td>7.1 ± 3.9</td>
</tr>
<tr>
<td></td>
<td>Expiration</td>
<td>6.2 ± 2.5</td>
<td>7.3 ± 2.9</td>
<td>5.5 ± 2.6</td>
</tr>
<tr>
<td>AB Male (n=7)</td>
<td>Inspiration</td>
<td>20.9 ± 11.6*</td>
<td>14.5 ± 8.6*</td>
<td>12.5 ± 9.2*</td>
</tr>
<tr>
<td></td>
<td>Expiration</td>
<td>11.1 ± 7.3*</td>
<td>10.3 ± 4.3*</td>
<td>9.2 ± 7.2*</td>
</tr>
</tbody>
</table>

Torques are presented for three body positions and two breathing conditions (inspired and expired). * indicates a difference (p<0.05) between the AB male group and the other two groups.

Discussion

Both the CoM and CoB were located approximately 4% higher in the impaired leg function swimmers than they were in the able-bodied male and able-bodied female swimmers. This finding can be attributed to anthropometric differences between the groups. The male and female impaired leg function swimmers were characterised by muscular atrophy of the lower limbs and pronounced muscularity of the upper body. This would cause a greater proportion of the impaired leg function swimmers' body mass and volume to be distributed in the upper body, compared to the able bodied male and female swimmers.

The CoM and CoB locations recorded for the able-bodied swimmers in the current study are very similar to those previously reported for competitive swimmers (McLean & Hinrichs 1998). In this earlier study, the CoM and CoB were located significantly higher in the males than in the females. In the current study, the CoM or CoB locations did not differ significantly between the able bodied male and female swimmers. This discrepancy may be due to anthropometric differences between the two studies’ participants. As expected, both the CoM and CoB moved higher up the body when the arms were moved from the sides of the body to full extension above the head. These findings are in agreement with those of previous studies (McLean & Hinrichs 1998; Gagnon & Montpetit 1981). In the current study, the displacement of the participants’ CoM and CoB towards their head, as the arms were extended overhead, were approximately 3% and 2%, respectively. This indicates that the arms comprised a greater proportion of a participant’s body mass than they did a participant’s body volume.

The buoyant torques recorded in this study are generally higher than those reported by Gagnon and Montpetit (1981). This may be due to anthropological differences between the studies’ participants or differences in testing protocols, for example, the level of inspiration and expiration used. The male swimmers (able-bodied and impaired leg function) experienced higher buoyant (leg-sinking) torques than the female swimmers (able-bodied and impaired leg function). This is in line with previous research findings (Gagnon & Montpetit 1981; McLean and Hinrichs 1998) and can be explained by sex differences in body mass distribution, specifically that females generally have a greater amount of adipose tissue, distributed in their thigh region, than males (McLean & Hinrichs 1998). As adipose tissue has a specific gravity less than one, a greater presence of it within a limb will enhance the buoyancy of that limb.

The female swimmers with impaired leg function experienced buoyant torques that were lower than those of their able-bodied female counterparts. The buoyant torques acting on the male impaired leg function swimmers were very similar to those for the able-bodied males. Competitive swimmers with
impaired leg function often compete in the same Para-swimming class as swimmers who are able to kick. Although this study has shown that swimmers with impaired leg function are no more prone to a leg-sinking torque than able-bodied swimmers of the same sex, their inability to kick will limit their means of counteracting the tendency of the legs to sink during free swimming. This may have implications for the energy cost of swimming for this impairment group. The results of this study may also contribute to the development of a more evidence-based classification system for swimmers with a disability.

**Conclusion**

Despite having a different body mass distribution, swimmers with impaired leg function do not experience a greater buoyant (leg-sinking) torque than able-bodied swimmers of the same sex.

**References**


**The evaluation of efficiency in the various leg-kicking techniques in scuba diving**

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**Introduction**

An awareness of the wide area in which scuba divers operate implies the setting of various goals for the activity which they perform. The aim of competitive fin swimming is to maximise the speed and rational expenditure of energy, allowing it to be maintained over the entire distance (McArdle et al. 2001). The lifeguard has to be as fast as possible when he is approaching the victim, yet a conscious economisation of the propulsive movements is necessary when towing and performing other rescue actions (Rejman et al. 2012). In recreational diving, while realising the hedonistic goals, what seems to be crucial is swimming comfort. Advanced scuba divers concentrate on minimising the consumption of the air they breathe in order to extend the diving time. The divers performing special tasks are required to demonstrate versatility in order to meet the goals of competitive fin swimming and swimming economisation in the form of rational breathing. The achievement of these goals is usually assessed through mechanical efficiency. The versatility of the goals mentioned requires a look at the efficiency of swimming over a wider scope – indicated by the sciences of efficient action (Kotarbinski 1965), which rests on the fundamental axiom that individual human beings act, that is, on the primordial fact that individuals engage in conscious actions toward chosen goals (Rothbard 1997).

Hence, the problem of the effective and economic use of fins for efficient swimming was considered in the utilitarian aspect, in order to adjust the technique of propulsive movements to the realisation of individual swimming goals.
The coherence of the definitions of efficiency (effectiveness and economisation) in different areas of scuba diving objectives (Figure 1) appears to justify the assumption that the efficiency of the swimming technique depends on the scuba diver’s ability to generate the maximal speed (effectiveness) and the skills to control it (economisation) for realisation of his own, individual goals.

![Diagram](image)

**Figure 1** Definition and formulas adapted from Kotarbinski (1965); McArdle et al., (2001); Zamparo et al. (2006) i Barbosa et al. (2010):

- \( \eta \) — mechanical efficiency;
- \( W \) — mechanical power;
- \( C \) — energy cost to cover one unit distance;
- \( E \) — energy expenditure corrected for body mass (Metabolic Power),
- \( v \) — swimming velocity.

Based on the physiological determinants of energy expenditure, the economy and effectiveness of fin swimming have been studied several times since Di Prampero, (1986). This area, in relation to the different dimension and stiffness of the fins, has been researched by Zamparo et al., (2002, 2006); Nicolas et al., (2007, 2009, 2010). Consistency of the aims for physiology, biomechanics and didactics provided by Barbosa et al. (2010) was reflected by employing the stroke length, stroke rate and Stroke Index to the analyses of the fin swimming. These parameters allow one to relate the technical skill of the swimmer (Cappaert 1999), increasing the economy of strength (Toussaint et al. 2006), limiting energy cost (Keskinen 1989), gives the opportunity for the swimmer’s energy conservation calculable as a function of race distances (Pendergast et al. 1996) while reducing fatigue, leading to the achievement and maintenance of maximal speed (Dekerle et al. 2005).

Only a few studies have been related to the effectiveness of the swimming rescue performed with fins (Abraldes et al. 2007; Rejman et. al. 2012). No trace of studies of other groups of swimmers using fins was found. The efficiency and economy of leg movements during flutter and dolphin-kick with fins were studied by Zamparo et al. (2002, 2006) and Rejman et. al. (2012). Yet no research was indentified concerning the propulsive movements using breaststroke-kick. The research area that had not been explored before was the source of formulation of the aim of the study—the analysis of the underwater leg propulsive movements performed using: flutter, dolphin and breaststroke-kick, with and without the diving equipment in terms of the assessment of the techniques mentioned. The aim was realised through verifying the indications resulting from the following research tasks: the assessment of the diagnostic value of the parameters applied to the evaluation of the swimming techniques analyzed; an investigation and assessment of the factors determining swimming efficiency and indication of the objective assumptions which enable the scuba divers to choose and adjust the swimming technique to the realisation of their own individual goals.
Material and methods

Eight male, professional scuba divers took part in the study. The certificate qualifying them for the Navy Diving Course was rationalised as an assumption that they presented a similar, high level of diving proficiency (skills). The somatic parameters of the subjects were also similar. All the procedures following the Declaration of Human Rights were met during the research.

The first task that they completed was to swim underwater (holding their breath) a 25 m distance in each of the three techniques: dolphin-kick, flutter-kick and breaststroke-kick with the fins. They swam (maximal speed) in natural prone position. The second task was performed under the same conditions, but the divers swam wearing diving equipment (buoyancy control jacket, regulator, diving cylinder, wetsuits). The divers used the same adjustable open heel type of fins (long, stiff,) and the same jacket, regulator and cylinder. The jacket was inflated in order to get the neutral buoyancy of each diver. The consecutive trials for each subject commenced only after heart rates returned to pre-exercise levels.

All the swimmers were filmed underwater with a digital camera in a waterproof box located in the middle of the long course pool, in order to record the divers and their fins on a sagittal plane (Rejman & Ochmann 2009). The calibration frame was treated as the reference system. Markers allowing the tracking of displacement of the hip joint were located on the divers’ bodies. The raw data recorded (sampling frequency – 50 Hz) were inputted to the Simi software (Simi Motion-Germany).

The intracycle velocity \( \nu_{av} \) was estimated and the mean values of stroke parameters (stroke length (SL) and stroke rate (SR)) were calculated. The Stroke Index (SI) and Index of Stabilisation of Intracycle Velocity were estimated. Stroke Index allowed for assessing the ability to generate maximum swimming velocity using the minimum number of the strokes (Costill et al. 1985). Thus, according the formula (1) the higher value of SI, the better the economics of swimming.

\[
SI = SL \cdot \nu_{av} \tag{1}
\]

\( \nu_{av} \) – Average horizontal velocity,

\( SL \) – Stroke length

The Index of Stabilisation of Intracycle Velocity (SVI) designed as the dimensionless measure of relative dispersion in the intracycle swimming velocity, describes the ability to avoid unnecessary drag by minimising the instantaneous acceleration/deceleration of the swimmers body through the water. It was based on the sum of the absolute values of the areas estimated under the curve of instantaneous swimming velocity as a function of time, bounded by the line corresponding to average velocity, and defined by Equation 2 (Figure 2, Equation 2).

As swimming speed increases, the drag the swimmer must swim against also increases, creating an increase in energy cost. That is why the average swimming velocity has been adopted as a measure of technique effectiveness. The SI has been categorised as a measure of the economisation of the propulsion generated in accordance to the criterion of velocity maximisation with the lowest number of strokes performed. The SVI illustrating the criterion for the minimisation of the drag forces through avoidance of the changes in intracycle velocity, has been adopted as a measure of the economisation of utilisation the propulsion which have been generated. In the context of the principle of the propulsion maximisation with the minimisation of the drag force, the effectiveness and economisation of the swimming technique may also be evaluated upon relation between SL and SR. This way the parameters mentioned could be justified to the assessment of the fin swimming techniques.
Explanation of procedure of the SVI estimation where: \( f(t) \) — instantaneous swimming velocity \((v_i)\) in the point of time \((t_i)\); \( f_{av} \) — average swimming velocity as the function of stroke time \((t_c)\); \( t_i \) — time recorded in the each sampling point; \( \alpha \) and \( \beta \) — the points limiting the stroke time \((t_j)\).

The analysis of the variation coefficients of the parameters described allowed employment of two-factor analysis of variance for dependent samples (ANOVA). The variables have been introduced in two groups of the qualitative predictors: techniques of propulsion (dolphin, flutter and breaststroke-kick) and diving equipment usage (swimming with and without equipment). The results obtained in the form of predicted average marginal have been standardised. The statistical significance of the differences has been evaluated by means of the Duncan’s post hoc test, creating the foundation for the research on the dependencies between the parameters studied (Spearman rank correlation).

Figure 2

\[
SVI = \frac{\frac{1}{\Delta t} \int_{t_i}^{t_f} [f(t) - f_{av}] dt}{f_{av} \cdot t_{c}}
\]
Results

Parameters estimated on the basis of Duncan’s post hoc test that were not been statistically different, are marked with a cross.

Figure 3 Graphs of the average marginal of the parameters studied for dolphin-kick, flutter-kick and breaststroke-kick with and without equipment, constructed on the basis of the results of the two-factor analysis of variance for dependent samples.

The results (Figure 3.) have suggested that swimming without equipment has outperformed swimming with equipment in terms of effectiveness ($v_{av}$), economisation of the propulsion generation (SI) and economisation of its utilisation (SVI). The values of the stroke parameters (SL and SR) were also higher when swimming without equipment. According to the aforementioned assumptions the dolphin-kick may be considered as the most effective. The indicators and stroke parameters have significantly differed from each other when swimming with and without equipment. Consequently, linking this fact with a similar velocity of the flutter/breaststroke-kick and the flutter/dolphin-kick, the most effective technique for the swimming with equipment has not been proved. Similarity of the Stroke Index has impelled a discussion on its diagnostic value in the assessment of the studied techniques.

The next stage of evaluation of the leg-kicking techniques (Figure 4) has been based on the dependencies between the predicated average marginal. The foundation for this assessment has been estimated by: rationality of the dependencies against the hydrodynamics principles and completeness of the parameters entering into relations, in a sense, where the elements work together in the mechanism of efficient propulsion. What was decided, is the minimisation of changes to the intracycle velocity (SVI) and the high value of the Stroke Index (SI) when swimming velocity increases ($v_{av}$) during dolphin and flutter-kick. In the case of the dolphin-kick, a high speed has been
achieved by lengthening the stroke (SL), correlated to a decrease in the stroke rate (SR) and in the flutter-kick – the SL lengthening correlated with the increase of SR. Therefore, when swimming the flutter-kick and the dolphin-kick without equipment, the high speed has been subordinated to the economisation of the propulsion generation and the economisation of its utilisation. The highest swimming speed in the breaststroke-kick has resulted from the minimisation of the changes in the intracycle velocity, and also the reduction of the SR, correlated to the SL lengthening. Thus in this technique the economisation of the propulsion utilisation only has been decided about the swimming effectiveness.

The correlation coefficients are plotted ($\alpha = 0.05$).

**Figure 4** The schemes illustrating the relations between the average marginal of the parameters that characterised the dolphin-kick, the flatter-kick and the breaststroke-kick test with and without the diving equipment

The dependencies in swimming with equipment (Figure 4) have not reflected the complete set of the elements working together in the mechanism for efficient propulsion. This mechanism in the dolphin-kick relied on the minimisation of the intracycle velocity changes (SVI) and the stroke economisation (SI) that resulted from the lengthening the stroke length, which correlated to the increase of the stroke rate. A velocity increase during the flutter-kick arose only from the minimisation of the velocity changes and an increase in the stroke rate. Whereas, in the breaststroke-kick, it was based on the stroke lengthening against the stroke economisation. That is surely why the effective dolphin-kick, directed to the high effectiveness ($v_{av}$), has rested on economisation of the generation (SI) and utilisation (SVI) of propulsion. In the flutter-kick the dependency with the SI has not been recorded, and in case of the breaststroke-kick the dependency with the SVI was not shown.

Taking into account and evaluating the parameters studied (Figures 3, 4) in the scope of the volume and intensity of the effort (Table 2), the analysis has been extended beyond the aspect of mechanical efficiency. From the point of enabling the divers to realise they own, autonomic goals when swimming without equipment, the dolphin-kick has been indicated as the most versatile technique. In swimming with equipment the flutter-kick has been the nearest to the realisation of the approved postulate.
Table 1  
Classification of the leg-kick techniques during swimming with and without equipment, from the point of enabling the scuba divers to realise their own, autonomic goals in the categories of volume and intensity of the effort

<table>
<thead>
<tr>
<th>SWIMMING EFFICIENCY</th>
<th>PROPELION GENERATED SI</th>
<th>PROPELION UTILIZED SVI</th>
<th>STROKE PARAMETERS</th>
<th>CATEGORIES OF SWIMMING GOALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFFECTIVENESS</td>
<td>Vr</td>
<td>Px</td>
<td>Str</td>
<td>Sf</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WITHOUT EQUIPMENT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highest fastest</td>
<td>Highest economization</td>
<td>Medium changes in velocity</td>
<td>Longest</td>
<td>Low high</td>
</tr>
<tr>
<td>Medium</td>
<td>Lowest changes in velocity</td>
<td>Highest</td>
<td>Shortest</td>
<td>Low MAX high</td>
</tr>
<tr>
<td>Lowest slowest</td>
<td>Highest changes in velocity</td>
<td>Medium</td>
<td>Lowest</td>
<td>Medium low</td>
</tr>
<tr>
<td>WITH EQUIPMENT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highest fastest</td>
<td>Lowest changes in velocity</td>
<td>Shortest</td>
<td>Highest</td>
<td>Low MAX high</td>
</tr>
<tr>
<td>Lowest slowest</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium medium</td>
<td>Medium low</td>
</tr>
</tbody>
</table>

Source: Maglischo (2003)

Note: The most versatile techniques in terms of efficiency (effectiveness and economy) are in bold (Dolph. – Dolphin kick, Flutt. – Flutter-kick, Brsts. – Breaststroke kick).

**Discussion**

During the evaluation of the flutter, dolphin and breaststroke-kick, with and without the diving equipment, one has to take into account the influence of the strategy of the control of the stroke parameters on the efficiency and the economy of fin swimming (Rejman et al. 2013). In the context of the challenged diagnostics value of the Stroke Index, (expressing the relation between the average swimming velocity and the stroke length) the stroke rate (in relation to the stroke length) has been labeled the factor determining the efficiency of fin swimming. Through the influence on the effectiveness and the economy of the propulsion generation, it allows for control of the changes in the intracycle swimming velocity in order to minimise it. The identified strategy for control of the stroke rate was different for the symmetrical (dolphin and breaststroke) and asymmetrical (flutter) kick without equipment. The most efficient dolphin-kick has been characterised by adjusting the stroke rate to the maintenance of the longest stroke possible, leading to obtaining the highest swimming speed at a stable level. The strategy of the breaststroke-kick has been similar, yet too low stroke rate decreased the economy of the propulsion generation and relatively high changes in the intracycle velocity limited the economisation of its utilisation. The flutter-kick, (performed at a higher stroke rate) has not been as effective as the dolphin-kick, probably as the result of the difficulty to maintain the stable velocity, leading to the production of the drag and decrease in the economisation of the propulsion utilisation. The highest efficiency of the dolphin-kick with diving equipment has probably been the consequence of the inertia induced by the additional mass of the cylinder set in motion by the undulating body (Colman 1999). Based on the results (Figure. 4), it can be judged that it resulted in the reduction of the intracycle swimming velocity changes (economisation of propulsion utilisation). Additionally, during the flutter-kick, (despite the same velocity), the relation between the stroke rate and the stroke length has not been recognised as in the dolphin-kick. What resulted was a decrease in the economisation of the propulsion. A lack of this relation has been observed also when comparing the flutter-kick and the breaststroke-kick. It produced an inefficient stroke lengthening in relation to the stroke rate and a higher velocity change. As it can be seen, the propulsion effect induced by the analyzed leg-kick techniques has been similar despite the different relations between the parameters examined. It creates an impression that the magnitude of the drag that occurs during swimming with equipment significantly reduces the possibility of efficient swimming. The comparable speed of the flutter and the breaststroke-kick confirms the need to show scuba divers the indications
enabling them to choose and adjust the propulsion technique in order to meet their own, individual goals.

The highest efficiency of the dolphin-kick without diving equipment is confirmed i.e. in the studies of Zamparo (2006). The analyses of swimming turns with and without the fins (Rejman 2008; Lyttle et al. 2000) and analysis of the propulsion generation of fish (Fish 2013) validated the results discussed in a wider scope. However, an analysis of the swimming rescue (Rejman 2012) helps to understand the doubts concerning the unambiguous assessment of efficiency of dolphin and flutter-kick, without regard for the equipment use factor. While approaching the victim, the dolphin-kick with fins were more efficient than flutter when towing (comparable to swimming with diving equipment). In this context it is justified to search for the indications above in a wider (not only mechanical) sense of the concepts of efficiency, effectiveness and economy. Zamparo et al., (2006) said that ‘economy needs efficiency but efficiency does not imply economy’. In the same meaning sounds the statement that efficient swimming is performed when most of the metabolic power is transformed into mechanical power, but usually only a part of the mechanical power is employed to propulsion, which in turn decreases swimming economy (Minetti 2004). But on the other hand, swimming is economical when the mechanical power output is adequate to all the possibilities of its utilisation for displacing the body at the current distance. An almost equal speed has been obtained as a result of the flutter-kick compared with dolphin and breaststroke-kick with equipment. So why negate a priori the breaststroke (or flutter) -kick as a source of propulsion during underwater swimming? What is more, it is well known that the swimmer who swims fast (effectively), generates a higher energy cost (less economy) than the swimmer who swims slower, thus the ratio of the velocity obtained to energy expenditure (efficiency) is lower for the faster swimmer. If these swimmers swim with the same velocity, a greater efficiency will be reached by the more skilled swimmer that generates a lower energy costs. In this context, the scuba divers’ individual preferences that result from the skills and the goals they established should determine the choice of the kicking technique. Indications that facilitate them such a rational choice can be stated on the basis of the volume and intensity of the effort performed. It categorises the level of the energy expenditure (in the physiological aspect), as simultaneously being the point of reference for the assessment of the individual swimming technique (Maglishcho 2003).

While treating the results as the recognition of the problem studied, it is justified to continue the research on a larger group of scuba divers. This study should be focused on defining the criteria for the technique of underwater swimming in relation to its efficiency measured with physiological markers, and to the deeper analysis of breaststroke-kick propulsion, which has not been studied before.

Conclusions

The efficiency of the fin swimming techniques studied can be developed by: the high level of utilisation of the propulsion generated (Index of Stabilisation of Intracycle Velocity), highly correlated with the strategy of control of the stroke rate without decreasing of the swimming effectiveness (velocity). However, the low level of the economisation of propulsion generation (Stroke Index) does not foster the efficiency of the fin swimming. The objective indications enabling the scuba divers to choose and adjust the technique of propulsive kicks to the realisation of the individual swimming goals can be determined according to the factors of efficiency of the propulsion and the stroke parameters in relation to the volume and intensity of the engaged effort.

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Effect of fatigue in spatiotemporal parameters during 100 m front-crawl event monitored through 3D dual-media automatic tracking

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Keywords: swimming, front crawl, dual-media kinematical tracking, fatigue

The purpose of the present study was to analyse the effect of fatigue on the three dimensional arm-stroke pattern during a 100 m front-crawl race. Six national level swimmers performed a 100 m front-crawl test at maximal intensity. The event was recorded with eight underwater and seven land cameras (Qualisys AB, Gothenburg, Sweden) using a full body retro-reflective marker setup. Swimming velocity, stroke frequency, stroke length, hand velocity, backward amplitude, amplitude slip, hand depth, width and range, and index of coordination were assessed for each 25 m lap. Differences between the four laps were analysed using a repeated measure ANOVA. Significant changes of analysed parameters were observed across the race, with exception of slip amplitude and hand depth, width and range. Thus, the analysis of spatiotemporal variables, under the influence of fatigue, should be understood as a relevant part of training monitoring aiming to increase performance, particularly when fatigue installs.

Introduction

Fatigue has been identified as a limiting factor in swimming with direct influence on performance. In short high-intensity swimming events performance could be compromised as a consequence of muscle force decrease, which characterise the specific fatigue of these events (Bonifazi et al. 1993 and Fitts 1994). Specifically during 100 m front-crawl all-out effort it was reported a decrease in power production as a fatigue consequence, inducing changes on general stroking biomechanical parameters (Toussaint et al. 2006).

Propulsion in front crawl depends essentially on arm-stroke motion (Deschodt et al. 1999), being particularly linked to horizontal and vertical forearms and hands kinematics (Berger et al. 1995). Hence, understanding how fatigue affects stroke kinematics throughout short swimming events could be of considerable interest to optimise performance. Nevertheless, studies regarding the effect of fatigue on 3D arm-stroke kinematics, during these efforts, are still limited. Suito et al. (2008) found a significant reduction in hand velocity and peak angular velocity of shoulder adduction from the first to the second half of the 100 m event, in agreement with the study of Toussaint et al. (2006).

The purpose of the present study was to analyse the effect of fatigue on 3D arm-stroke kinematics during a 100 m front-crawl performed at maximal intensity.

Methods

Six trained male swimmers (mean ± SD: age 25.47 ± 4.69 years, height 1.82 ± 0.04 m, body mass 73.14 ± 6.14 kg, years of training background 12.47 ± 5.43, a training frequency higher than 7 training units
per week and performance at the 100 m front crawl world record 86.34 ± 3.41%) participated in the study. Testing took place in a 25 m indoor pool, 1.90 m deep, with a water temperature of 27.5 °C. After a moderate intensity individual warm-up, subjects performed a 100 m front-crawl maximal effort, from a push off start and using open turns to eliminate the influence of the dive and gliding in the analysis of stroke cycle. The event was recorded using seven land and eight underwater cameras (Oqus 3+ and Oqus Underwater, Qualisys AB, Gothenburg, Sweden) operating at 60 Hz. The calibrated volume was defined using three calibrations – underwater, overwater and twin (to merge the first and the latter) – according to manufacturer’s guidelines. Orthogonal axes were defined as x for the direction of swimming, y for the mediolateral direction and z for the vertical, where z=0 defines the water surface.

Data acquisition was performed with Qualisys Track Manager version 2.7 (Qualisys AB, Gothenburg, Sweden) and data post processing employed Visual3D (C-Motion, Germantown, MD, USA) using low pass digital filter of 6 Hz. Each swimmer was equipped with a full body retro-reflective marker setup. Acromion, lateral and medial humerus epicondyle, radius- and ulna-styloid processes, third distal phalanx, iliac crest, and anterior and posterior iliac spine, for both right and left sides, were the anatomical reference points selected. Figure 1 exhibits the marker setup and its different stages throughout the data acquisition and post processing procedure.

![Figure 1](image)

**Figure 1** Full-body marker setup: (a) swimmer, (b) acquired in Qualisys Track Manager, and (c) post-processed using Visual3D.

For the data analysis the front-crawl arm movements were split into four phases (adapted from Chollet et al. 2000), determined from the swimmer’s x and z positions of the hand centre of mass (CM) and acromion: (i) entry and catch, between the first z negative coordinate and the beginning of the backward movement of the hand CM; (ii) pull, from the end of the entry and catch phase until the mid-underwater stroke position, determined by coincident x positions of hand CM and acromion; (iii) push, from the end of the pull until the hand release from the water, determined by the z positive coordinate of hand CM after the underwater trajectory; and (iv) recovery, from the end of the push until re-entry into the water of the hand CM.

For each 25 m lap, stroke frequency (SF) was assessed by the inverse of the time needed to complete one stroke cycle and the stroke length (SL) by the horizontal displacement of the pelvis CM. The mean velocity was computed by dividing the swimmer’s average pelvis CM horizontal displacement by the time required to complete one stroke cycle.

The backward displacement and slip amplitudes were calculated through the difference between the coordinates of the most forward point and the most backward position of the hand CM, and of the
entry and exit of the hand CM, respectively. The maximum hand depth was defined as the most negative vertical coordinate of the hand CM. The maximum hand width was defined as the maximum lateral coordinate of the hand CM with respect to the pelvis CM and the hand range calculated as the difference between the maximum and minimum lateral coordinates of hand CM at the pull phase with respect to the pelvis CM. Arm coordination was quantified using the index of coordination (IdC), which measures the lag time between the propulsive phases of the arms action, and was expressed as the percentage of the overall duration of the stroke cycle (cf. Chollet et al. 2000). Differences between the four laps were considered using a repeated measure ANOVA with LSD post-hoc test (p<0.05).

Results

Mean±SD, p-value, and partial $\eta^2$ of ANOVA are displayed in Table 1 for general biomechanical parameters and, in Table 2, for the arm lengths and coordination.

Changes of analysed parameters were observed across the race as denoted by the significance level and high effect sizes.

Table 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Lap 1</th>
<th>Lap 2</th>
<th>Lap 3</th>
<th>Lap 4</th>
<th>p</th>
<th>Partial $\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m.s$^{-1}$)</td>
<td>1.53±0.07</td>
<td>1.45±0.08$^a$</td>
<td>1.33±0.05$^{a,b}$</td>
<td>1.33±0.07$^{a,b}$</td>
<td>&lt; 0.001</td>
<td>0.83</td>
</tr>
<tr>
<td>Stroke frequency (Hz)</td>
<td>0.77±0.08</td>
<td>0.74±0.07</td>
<td>0.69±0.06</td>
<td>0.73±0.04$^c$</td>
<td>0.04</td>
<td>0.42</td>
</tr>
<tr>
<td>Stroke length (m)</td>
<td>1.98±0.16</td>
<td>1.97±0.22</td>
<td>1.96±0.13</td>
<td>1.83±0.16$^{a,b,c}$</td>
<td>0.01</td>
<td>0.51</td>
</tr>
<tr>
<td>Hand velocity (m.s$^{-1}$)</td>
<td>2.40±0.22</td>
<td>2.30±0.25$^a$</td>
<td>2.12±0.18$^{a,b}$</td>
<td>2.07±0.14$^{a,b}$</td>
<td>&lt; 0.001</td>
<td>0.84</td>
</tr>
</tbody>
</table>

$^{a,b,c}$Significantly different from the first, second and third lap, respectively. p<0.05.

Swimming velocity, SL, and hand velocity decreased along the 100 m. Contrarily, SF (last lap), backward amplitude and IdC (catch up coordination mode) increased.

No alterations of amplitude slip, hand depth, width and range were observed throughout the effort.

Table 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Lap 1</th>
<th>Lap 2</th>
<th>Lap 3</th>
<th>Lap 4</th>
<th>p</th>
<th>Partial $\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backward amplitude (m)</td>
<td>0.53±0.06</td>
<td>0.55±0.05</td>
<td>0.53±0.04</td>
<td>0.56±0.04$^{a,c}$</td>
<td>0.005</td>
<td>0.56</td>
</tr>
<tr>
<td>Amplitude slip (m)</td>
<td>0.12±0.14</td>
<td>0.10±0.15</td>
<td>0.07±0.24</td>
<td>0.03±0.15</td>
<td>0.25</td>
<td>0.24</td>
</tr>
<tr>
<td>Hand depth (m)</td>
<td>-0.60±0.07</td>
<td>-0.60±0.06</td>
<td>-0.61±0.08</td>
<td>-0.60±0.07</td>
<td>0.59</td>
<td>0.11</td>
</tr>
<tr>
<td>Hand width (m)</td>
<td>0.38±0.13</td>
<td>0.35±0.11</td>
<td>0.39±0.11</td>
<td>0.37±0.08</td>
<td>0.32</td>
<td>0.25</td>
</tr>
<tr>
<td>Hand range (m)</td>
<td>0.31±0.09</td>
<td>0.30±0.09</td>
<td>0.33±0.08</td>
<td>0.33±0.08</td>
<td>0.36</td>
<td>0.37</td>
</tr>
<tr>
<td>Index of coordination</td>
<td>-10.28±2.22</td>
<td>-11.59±3.00</td>
<td>-10.15±4.20</td>
<td>-8.09±3.34$^{a,b}$</td>
<td>0.04</td>
<td>0.43</td>
</tr>
</tbody>
</table>

$^{a,b}$Significantly different from the first, second and third lap, respectively. p<0.05.

Discussion

The stroking parameters changed throughout the 100 m front crawl race as expected, in accordance with literature (Chollet et al. 1997; Vorontsov & Binevsky 2003; Seifert et al. 2005; Toussaint et al. 2006). Swimming velocity declined along the event as an effect of SL decrease (with statistical significance in the last lap), probably due to fatigue, which probably disabled swimmers to apply the same level of propulsive force, or to prevent drag, throughout the stroke towards the end of the race (Craig et al. 1985; Keskinen & Komi 1993). SF showed a tendency to decrease until the third lap, but increased at the last 50m to compensate the decrease in SL, as an attempt to maintain velocity (Chollet et al. 1997; Alberty et al. 2008). Concomitant with velocity decrease, hand velocity diminished along the effort, as previously observed (Suito et al. 2008; Toussaint et al. 2006) likely due to the inability to maintain mechanical and muscular features (Aujouannet et al. 2006). This fact
suggests that decreases in swimming velocity are probably caused by lower hand velocities, as it is considered to be one of the main propelling body segments in front-crawl technique (Suito et al. 2008).

Swimmers presented a catch up coordination mode during the 100 m race. In addition, as velocity and SL/SF ratio changed along the event, swimmers tended to adapt their IdC, in the final stages, by diminishing the lag time between propulsive phases, a fact that reveals the development of fatigue, as reported previously (Seifert et al. 2005; Alberty et al. 2005; Alberty et al. 2008). Moreover, backward amplitude increased in the final lap suggesting that the forward point was likely increased once fatigued swimmers tended to augment the time during the entry phase, with the arm extended, before beginning the pull (Goldfuss & Nelson 1971; Aujouannet et al. 2006).

Values of hand depth, width and range were maintained stable throughout the effort, being similar to those presented previously for a 200 m maximal effort (Figueiredo et al. 2013). Therefore, even considering the impairments imposed by fatigue, it is suggested that swimmers adapt their coordination, rather than stroke pattern, as a response to overcome fatigue.

Conclusion
The present findings showed that the swimmers’ arm-stroke motion was altered by the induced fatigue. This fact could be useful for coaches and swimmers to understand the effects of fatigue on technical parameters of front crawl technique, as way to improve performance. Moreover, it showed that dual-media automatic tracking can be used successfully for Motion Capture of swimmers.

Acknowledgments
This investigation was supported by grants of Portuguese Science and Technology Foundation: PTDC/DES/101224/2008 (FCOMP-01-0124-FEDER-009577) and SFRH/BD/81337/2011.

References


Variability in coach assessments of technique in front crawl sprint swimming

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Keywords: competitive swimming, swim coaching, freestyle characteristics

Introduction

Competitive swim performance is assessed by total race time and can be analysed to comprise of three components. The first is the start time, the second is the time spent free swimming and the third is the turn performance time. In competitive swimming, free swimming occupies the most time during an event. Improvements in free swimming performance can therefore have considerable influence on overall race time. The front crawl technique has evolved into the fastest of the four competitive styles of swimming and is made up of a right and left arm-stroke cycles with a varying number of kicks (Maglischo 2003). Seifert, Chollet and Chatard (2007) suggest that there are four main phases of an arm-stroke cycle which include: 1) entry and catch, 2) pull, 3) push, and 4) exit and recovery. Chollet, Chalis and Chatard (2000) also outlined that the phases which generate propulsion during the stroke are the pull and push phases. There has been much debate amongst scientists on what is the most correct or efficient technique in front crawl swimming (Rushall, Holt, Sprigings & Cappaert 1994). For instance, what path the hand should take through the water or how wide the hand should be relative to the shoulder during the pull and recovery phases. Most coaches have different views on what is considered good and poor front crawl technique. Furthermore, notable variations exist in front crawl swimming technique between competitors at the elite level. For example, different styles of front crawl swimming include a smooth and consistent stroke, a slight catch-up stroke pattern or a straighter arm pull technique. A search of the literature found no investigations which assessed the variability between elite coaches regarding their perception of good and poor front crawl swimming technique. In the absence of such data, a comparative study seemed warranted. Therefore, the aim of this investigation was to compare coach ratings of front crawl sprint swimmers to examine the degree of variability between their assessments of front crawl technique.

Method

The front crawl sprint performance of 12 State and National level swimmers (8 males and 4 females; 19.83 ± 2.55 years: 100 m FINA points ranking 698 ± 70; 100 m freestyle performance time 54.61 ± 4.17 s) were video recorded and analysed in this study. Seven elite level coaches (2 Gold and 5 Silver Australian Swim Coaching Licence) were asked to rate all twelve swimmer’s techniques. Federation Internationale de Natation (FINA) point rankings refer to a score given to a swimmer’s performance
time in relation to the current world record. Ethical approval was obtained from both the Australian
Institute of Sport and the University of Canberra Ethics Committees and both coaches and swimmers
provided their written informed consent prior to participation. In the case of minors, parental or
guardian consent was obtained.

The swimmers were video recorded from two camera views, a head-on (Figure 1) and a side-on
(Figure 2) view. The side-on above and underwater cameras were mixed with an Edirol video mixer
(EDI-V8) to produce a single moving above/below image. A digital time-code was applied to both
camera inputs to allow accurate deconstructions of a stroke cycle into the four phases used in the
analysis. Of the four stroke phases outline by Seifert, et al. (2007), the pull and push phases were
analysed.

Figure 1  Example of a head-on view

Figure 2  Example of a side-on view

Coaches were then provided with survey sheets (Figure 3) which included still images, captured from
the video footage, of each swimmer at each of the stroke phases on both the right and left arm
strokes. The coaches were also asked to give an overall technique rating from head-on and side-on
video footage. Ratings were obtained by placing an X on a Likert Scale (McLeod 2008). The scale the
coaches were asked to rate the swim technique on was a horizontal line of 20 cm in length with a range indicated from ‘poor’ to ‘excellent’. Coach rating of technique was then quantified by measuring the distance from the left end of the line to the marked X and recorded in cm. Correlational analysis was performed to determine the relationships between overall coach ratings averages and swim performance measures (FINA point rank and performance time). Individual coach ratings were correlated against swim performance measures to determine if coach agreement was similar as an overall rate and when assessing the stroke at the pull and push phases. Coaches who demonstrated good agreement were included in the individual assessments. Coaches who were perceived as outliers were withdrawn from the individual assessments. Cronbach’s alpha (α) was used to further explore the inter-rated variability between coach ratings.

![Example of survey](image)

**Results**

Mean coach overall rating of technique demonstrated a statistically significantly agreement with both FINA point rankings ($r = 0.69$, $p = 0.023$) and personal best times ($r = -0.75$, $p = 0.005$). Figure 4 demonstrates the positive correlation of coach ratings against FINA point ranking, whereas Figure 5 reveals a negative correlation of coach ratings against 100 m performance best times.
When correlating overall technique using the individual coach ratings an inverse relationship for coach 1 was revealed in comparison to the other six coaches. Coach 1 was therefore considered an outlier and not included in the individual assessments. Table 1 reveals the range of individual coach ratings across the right pull, right phase, left pull and left push phases against the performance measures. Cronbach's alpha (\( \alpha = 0.615 \)) indicated a moderate level of consistency between coaches overall rating scores (n = 6).

**Table 1** Correlations (shown as r values) demonstrating the individual coach rate compared to the performance measures (FINA point score (FINA pts) and 100 m Performance Time (PT))

<table>
<thead>
<tr>
<th></th>
<th>Right Pull</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FINA pts</td>
<td>100m PT</td>
<td>FINA pts</td>
<td>100m PT</td>
<td>FINA pts</td>
<td>100m PT</td>
<td>FINA pts</td>
</tr>
<tr>
<td>Coach 2</td>
<td>-0.21</td>
<td>0.10</td>
<td>-0.13</td>
<td>0.25</td>
<td>0.04</td>
<td>-0.15</td>
<td>-0.05</td>
</tr>
<tr>
<td>Coach 3</td>
<td>0.46</td>
<td>-0.37</td>
<td>0.01</td>
<td>0.07</td>
<td>0.25</td>
<td>-0.22</td>
<td>0.32</td>
</tr>
<tr>
<td>Coach 4</td>
<td>0.29</td>
<td>-0.08</td>
<td>0.21</td>
<td>0.00</td>
<td>0.29</td>
<td>0.00</td>
<td>-0.13</td>
</tr>
<tr>
<td>Coach 5</td>
<td>0.14</td>
<td>-0.11</td>
<td>0.06</td>
<td>-0.01</td>
<td>-0.12</td>
<td>0.19</td>
<td>-0.31</td>
</tr>
<tr>
<td>Coach 6</td>
<td>0.03</td>
<td>-0.12</td>
<td>0.01</td>
<td>-0.02</td>
<td>0.4</td>
<td>-0.11</td>
<td>0.01</td>
</tr>
<tr>
<td>Coach 7</td>
<td>0.36</td>
<td>-0.55</td>
<td>0.43</td>
<td>-0.42</td>
<td>0.44</td>
<td>-0.37</td>
<td>0.38</td>
</tr>
</tbody>
</table>
**Discussion**

This investigation compared coach ratings of front crawl sprint swimmers to examine the degree of variability between their assessments of front crawl technique. Results indicated good agreement between coach rating of overall technique and the performance level of the swimmer. This finding suggests that for this sample of coaches, their perceptions of poor and good technique are related to the quality of swim performance. Thus, these coaches are likely to be able to identify faults and correct stroke techniques that could result in improvements.

Assessment of the variability between individual coach ratings demonstrated moderate to high variability (see Table 1) against performance measures. This suggests that individual variation existed between coach opinion of poor and good technique. All six remaining coaches in the current study were highly qualified and possessed considerable coaching experience. Thus, the variation in coach opinion could explain the notable variation that exists in front crawl technique at the elite level.

A limitation of this pilot study is the relatively low number of coaches involved. Further study should be conducted to gain a greater insight into how coaches rate front crawl performance according to what licence they hold and what level of swimmers they have previously coached. Furthermore, when pursuing future research, screening a subset of coaches who have highly correlated ratings is recommended if intending to use coach ratings as a measure of technique quality.

**References**


**How competitors increase their velocity: examination on spatio-temporal, coordination and kinetic parameters**

**Ludovic Seifert**¹, **Christophe Schnitzler**², **Huub M Toussaint**³, **Chris Button**⁴

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**Keywords:** adaptation, arm coordination, front crawl, kinetic

**Abstract**

We aimed to examine how swimmers modify their velocities as a function of swim pace using spatio-temporal and kinetic data. In a group of 12 competitive swimmers, swim speed (v), stroke rate (SR), stroke length (SL), Index of coordination (IdC) and propulsive phase duration (PrP) were determined using four underwater cameras. Force impulse per stroke (I⁺/stroke) and average force (Faverage) were determined using eight force sensors attached to both sides of the dominant hand. Results show that to swim faster, participants increased SR, IdC, PrP and Faverage (p<0.05). Movement coordination patterns were reorganised while hand forces were scaled, enabling swimmers to keep I⁺/stroke constant despite propulsive time decreasing across stroke.
Introduction

Propulsion in front crawl swimming can be broken down into a series of propulsive impulses ($I^+/\text{prop}$), while the forward progress of the swimmer will in return generate a series of resistive impulses ($I^-/\text{stroke}$) \(^{(1)}\). When swimming at constant speed, equation 1 applies

\[ I^+/\text{prop} = -I^-/\text{stroke} \]  \hspace{1cm} \text{(equation 1)}

While $I^-/\text{stroke}$ is generated throughout the swim cycle, $I^+/\text{prop}$ is only generated during the propulsive phases of the arms during the stroke cycle.

Chollet et al. (2000) decomposed the arm movements in front crawl. It was described as a succession of different phases: catch, push, pull, and recovery, with pull and push being the propulsive phases (PrP), hence only a part of the cycle. According to Alberty et al. (2009), the propulsive forces contributed by both arms can be calculated as:

\[ I^+/\text{prop} = I^+_{\text{r}} + I^+_{\text{l}} = F_{\text{r}} \cdot (T_{\text{pullr}} + T_{\text{pushr}}) + F_{\text{l}} \cdot (T_{\text{pulll}} + T_{\text{pushl}}) \]  \hspace{1cm} \text{(equation 2)}

where $F$ denotes the cycle averaged propulsive force of the arm, and $T_{\text{pull}}$ and $T_{\text{push}}$ the time in which propulsive force is generated.

Chollet et al. (2000) quantified the lag time between two successive propulsive phases of each arm with an Index of Coordination. Several studies have subsequently shown that at low velocity a gliding time is typically observed within the swim cycle (so IdC<0). In contrast, at fast velocities, propulsive impulse from right and left arm can overlap (so IdC>0). Hence, recalling Alberty et al. (2009)

\[ I^+/\text{prop} = F_{\text{prop}} \cdot T_{\text{cycle}} \cdot (100\% + 2 \cdot \text{IdC}) \]  \hspace{1cm} \text{(equation 3)}

$I^+/\text{prop}$: Positive impulse $T_{\text{cycle}}$: cycle duration; IdC: index of coordination

Consequently, to swim faster, swimmer can either increase $F_{\text{prop}}$, $T_{\text{cycle}}$, IdC, or any combination of these parameters. In general, skilled swimmers maximise time allotted to propulsion by increasing SR, but also PrP and IdC (Seifert et al. 2004a,b); and also that they are capable of exhibiting the highest values of IdC and PrP. However, Schnitzler et al. (2011) found contradictory results in 400m, in which better swimmers were characterised by lower IdC’s, suggesting that higher $I^-/\text{stroke}$ were obtained thanks to higher $F_{\text{prop}}$. But in these studies $I^-/\text{stroke}$ was inferred from coordination and spatio-temporal data, and not measured directly.

The aim of this study is to understand the strategies that are applied by swimmers to change their velocity. By studying both arms coordination and kinetic parameters simultaneously. We hypothesised to swim faster, swimmers tend to increase propulsive continuity of motor action and increase the overall force impulse.

Methods

A convenience sample of eleven male swimmers (age: 22.5±7.4 years) participated in the present study. All were competitors. Before the experiment, a brief interview with each swimmer verified the absence of injuries and diseases. The study was approved in advance by the participating institution’s Human Ethics Committee.

The swim trials took place in a motorised aquatic flume in a temperature- and humidity-controlled laboratory environment. After a standardised 20-min warm-up, their maximal swim velocity ($V_{\text{max}}$) in the flume was determined. Three individual-specific velocities relative to $V_{\text{max}}$ or paces, were determined: $V_1$ (60%), $V_2$ (85%), and $V_3$ (100% of $V_{\text{max}}$). The subjects swam 20 s at $V_1$, $V_2$, and 10 s at $V_3$.

Video analysis was used to determine spatio-temporal (swim speed, stroke rate, stroke length) and coordination (IdC, PrP) using the protocol described by Schnitzler et al. (2011). To measure forces
acting on the swimmer’s hand, four pairs of pressure sensors were glued to the surface of a glove on both the palmer and dorsal sides of metacarpophalangeals II, III, IV, and V. Force was measured in units of 0.001 N (0.1 g). After calibration of pairs of sensors within the water, in-motion mean pressure was obtained using equation Equation 5, as described by Takagi and Wilson (1998).

\[
\text{P}_{\text{mean}} = 0.045P_A + 0.186 P_B + 0.554 P_C + 0.013 P_D + 7.558
\]

The obtained value was then multiplied by the hand plane area \((m^2)\) to calculate the resultant propulsive force. The force impulse was calculated by numerical computation of the area under the force-time data. Video footage ensured that the two peaks were measured during the pull and push phases. Only non-breathing cycles were taken into consideration for measurements.

After initial check of the normality of distribution (Ryan Joiner test) and the homogeneity of variance (Bartlett’s test), a series of two-ways ANOVAs for repeated measures [repeated factor: subject] were used to compare the mean values for each variable as a function of pace. To detect significant differences, Tukey’s post hoc tests were used. The threshold for significance was set at the 0.05 level of confidence. For the statistical analysis, Matlab 8.1 was used.

**Results**

Table 1 presents the result for spatio-temporal and coordination parameters, whereas Table 2 presents force kinetic parameters.

### Table 1: Spatio-temporal and coordination parameter as a function of swim pace

<table>
<thead>
<tr>
<th>Pace</th>
<th>SR (stroke.min-1)</th>
<th>SL (m)</th>
<th>IdC (%)</th>
<th>PrP (%)</th>
<th>PrP (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pace 1</td>
<td>32.7±5.7b,c</td>
<td>1.85±0.39</td>
<td>-2.5±6.1c</td>
<td>47.1±6.0c</td>
<td>0.89±0.17b,c</td>
</tr>
<tr>
<td>Pace 2</td>
<td>41.4±5.5a c</td>
<td>1.87±0.37</td>
<td>-0.5±6.8c</td>
<td>49.1±6.7</td>
<td>0.72±0.12a</td>
</tr>
<tr>
<td>Pace 3</td>
<td>49.1±6.2a,b</td>
<td>1.9±0.28</td>
<td>4.0±7.0a,b</td>
<td>54.3±7.6a</td>
<td>0.67±0.11a</td>
</tr>
</tbody>
</table>

Significant difference with a: Pace 1  b: Pace 2  c: Pace 3

### Table 2: Kinetic parameters as a function of swim pace

<table>
<thead>
<tr>
<th>Pace</th>
<th>t'/stroke (N.s)</th>
<th>F_{average} (N)</th>
<th>F pull (N)</th>
<th>F push (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pace 1</td>
<td>40.8±8.8</td>
<td>22.26±6.34b,c</td>
<td>56.5±19.8c</td>
<td>70.5±21c</td>
</tr>
<tr>
<td>Pace 2</td>
<td>42.7±8.7</td>
<td>29.03±6.27a</td>
<td>66.0±16.8</td>
<td>84.3±17.1</td>
</tr>
<tr>
<td>Pace 3</td>
<td>40.7±10.4</td>
<td>32.94±8.31a</td>
<td>73.2±22.8a</td>
<td>87.9±23a</td>
</tr>
</tbody>
</table>

**Discussion**

The objective of this study was to examine and compare the motor strategies used by competitive swimmers to increase their swim speed. We found that competitive swimmers tend to maintain the overall force impulse by altering coordination parameters and force development within the cycle. The increase in stroke rate contributes to the increase in average force developed during each cycle.

In accordance with our results, past studies showed that swimming faster implies an increase in stroke rate (SR) and coordination parameters (IdC, PrP) (Chollet et al. 2000; Seifert et al. 2004a) and the average force developed by the hand in the water (Rouard et al. 1992). Doing that, not only is the number of impulse over the distance increased, but also the time allotted to propulsion within the cycle maximised, thanks to a modification of the coordination parameters within the stroke. What is not known is how these kinematic changes influence kinetic parameters within the stroke. Our force data show that the overall \( t' / \text{stroke} \) is kept constant, despite the fact that the absolute time devoted to propulsion decreased with swim speed. In other words, to maintain the impulse constant despite a shorter duration, several changes have to be made within the stroke organisation. In accordance with
past studies (Monteil et al. 1994), the relative durations of the non-propulsive phases were shortened, whereas higher peak forces were developed during pull and push phase.

So to summarise, to swim faster, swimmers increase the average force maintained over time by maximising the number of propulsive impulse, that is, by increasing SR, whereas the more in-depth reorganisation of the stroke (IdC, PrP) helps keep the overall impulse per stroke ($I_{\text{stroke}}$) constant despite the decrease in absolute propulsive time.

Recording simultaneously kinematic and kinetic parameters provides a promising perspective to understand swim adaptation mechanisms. This study however presents some technical and methodological limitations. From the technical point of view, our protocol only allowed force measurement on one arm. Therefore, we assumed that force development was comparable from left to right side, which might not be the case (Tourny-Chollet et al. 2009). This is why we chose to put the sensor on the dominant hand of each swimmer, to be at least capable of comparing force-time curves between swimmers. This technical limitation also had an implication on the determination of $I_{\text{stroke}}$. But when propulsive force overlap - as was the case in recreational and expert swimmers - $I_{\text{stroke}}$ mechanically increased, and this difference in $I_{\text{stroke}}$ might in fact reach significance. However, this would not change the conclusion that the modification of spatio-temporal and coordination parameter help to maintain the propulsive impulse of one arm constant despite a change in the absolute duration of propulsive phase.

Conclusion

Taken together, our findings demonstrate that to swim faster, swimmers change their behaviour in a systemic manner and at different scale: they modify coordination parameters to maintain the $I+/\text{stroke}$ constant at arm’s level, and increase their stroke rate to multiply the frequency of the force impulses per stroke, thus increasing $F_{\text{prop}}$. It would now be interesting to assess inter-individual variability to examine if these adaptations to swim pace can be related to individual strategies.

References


How competitive swimmers adapt their inter-limb coordination to drag perturbation

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Abstract
The aim of this study was to examine the adaptability of the limbs movements and arm-leg coordination pattern in expert breaststroke swimmers when a drag perturbation is artificially applied. Six competitive swimmers performed an intermittent flume test composed of three randomised stages (60%, 70%, 80% of their maximal speed). Each stage consists of swimming 15 cycles at the given speed, then the swimmer was towed with a cable 1m backward from his initial place. Immediately after, the swimmer had to return as fast as possible to his initial place, before continuing to swim for 15 further cycles. Four inertial measurement units assessed elbow and knee angles, in order to calculate elbow-knee relative phase. The results suggest that there was a similar effect of the perturbation on the task-goal outcome and the behaviour outcome as the swimmer took similar number of cycle to recover the 1m and initial coordination pattern. However, large inter-individual variability was observed at 80% of maximal speed supporting that high active drag led to individual adaptation strategies.

Introduction
Swimming skill is mostly analysed in terms of performance outcomes (i.e., time for a given distance). But understanding expertise goes beyond the ‘how fast can you swim’ question. Adaptability, considered as the capacity of expert to modify their behaviour to respond to subtle modification in the constraint acting on them, might also be a key concept of expertise to investigate (Seifert, Button & Davids 2013). According (Newell 1986), individuals interact with three types of constraints: environmental, task and organismic constraints. In swimming, environmental constraints could be exemplified by change in the water flow, wave, active drag; task constraints could relate to swim pace, imposed stroke rate, to reach a ball in water polo, to achieve a certain body position in synchronised swimming; finally, organismic constraints could concern the impact of size, shape and density of the body and its segments. By artificially generating perturbation to the swim stroke, it can be explored how expert swimmers adapt their limbs movements and limb coordination pattern to constraints, brought about by a subtle blend between behavioural stability and flexibility. According to (Li, Haddad & Hamill 2005), stability corresponds to the capability and the time an individual takes to resist to a perturbation or to recover his initial motor behaviour after perturbation (e.g., assessed by the relaxation time (Kelso, Scholz & Schöner 1987)). Flexibility relates to the fluctuations within a coordinative pattern to continually adapt to a given set of constraints. From there, adaptability corresponds to the ratio between behavioural stability and flexibility, in the sense where an adaptive swimmer is stable when it’s needed and is flexible when it’s needed, supporting functional movement and coordination variability. From there, the aim of this study was to examine the adaptability of the limbs movements and coordination pattern in expert swimmers when a drag perturbation is artificially applied.

Methods
Six competitive male swimmers performed an intermittent flume test composed of three randomised stages (60% (S60), 70% (S70), 80% (S80) of maximum speed) with four minutes of rest between stages. The participants started with a familiarisation session in the flume where the maximal speed was determined during a 10s maximal effort (average maximal speed was 1.28 ± 0.06 m.s⁻¹). Two days after, the testing started with a regular warm-up of 20minutes, then the swimmers were requested to familiarise with the target speed of each stage: S60 was 0.75 ± 0.05 m.s⁻¹; S70 was 0.88 ± 0.06 m.s⁻¹;
S80 was 1 ± 0.07 m.s⁻¹. Each stage consisted of swimming breaststroke at a predetermined location (above a line marked on the floor of the flume) for fifteen cycles at the given speed; then a drag perturbation was applied (the swimmer was towed with a cable 1m backward from the line; the cable was attached to a dynamometer in order to control the applied towing force). Immediately after, the swimmer had to return as fast as possible to above the line, before continuing to swim for ten further cycles. One lateral camera recorded the number of cycles to recover to the line after the perturbation. Four inertial measurement units located on the forearm and the arm to assess elbow angle, and on the thigh and the leg to assess knee angle in breaststroke swimming. These IMUs were positioned on the left side of the swimmers: on the forearm (posterior surface of the proximal portion), the arm (posterior surface of the distal portion), the thigh (anterior surface of the distal portion) and the leg (anterior surface of the proximal portion), in order to place the sensors in direct contact with a bony part of the limb. The two limbs equipped with sensors wore strands of swimsuits in order to limit resistances due to the presence of the sensors. Prior to testing, the swimmers performed a vertical jump without flexing the leg to permit detection of simultaneous vertical acceleration in the four IMUs, for synchronisation purposes. Each IMU corresponded to a combination of a tri-axial accelerometer (+/-8G), tri-axial gyroscope (160°/s) and a tri-axial magnetometer (MotionLog, Movea©, Grenoble, France), with 200Hz rate sampling. Data were recorded with North magnetic references and computed with MoveaLab software (Movea©, Grenoble, France). The cycle duration (and the stroke rate in Hertz was obtained as follows: 1/cycle duration) and angle were computed as an integration of the gyroscope measure. This integration makes the measurement highly prone to drift. To correct that drift, wrapping lines were computed around the angle signal, then the signal was normalised with the support of these reference lines (for more details(Seifert, Komar & Hérault 2014)). This data processing did not allow getting absolute value of knee and elbow angle but only relative angle (θrel) that was normalised between -1 and +1 (Hamill, Haddad & Mcdermott 2000), while cycle duration was also resampled in 100%. Knee and elbow angular velocities (ωrel) were also normalised in the interval [-1, +1]. Then, phase angles (φelbow and φknee) in degrees were afterward calculated and corrected according to their quadrant (Hamill et al. 2000): φ = arctan (ωrel / θrel). Finally, the continuous relative phase for a complete cycle was calculated as the difference between both phase angles (Hamill et al. 2000): φrel = φelbow - φknee. Theoretically, two extreme modes of coordination are possible: in-phase (φrel = 0°) and anti-phase (φrel = 180°); however, following previous study (Seifert et al. 2011) on inter-limb coordination, a lag of ± 30° was accepted to define the adopted coordination pattern. Therefore, an in-phase mode was assumed to occur when -30° < φrel > 30°, while an anti-phase mode was defined by -180° < φrel > -150° and 150° < φrel > 180°. From there, elbow-knee coordination flexibility was measured by comparing the φrel standard deviation of ten cycles prior to and after the perturbation. The stability of elbow and knee angles, and elbow-knee coordination was assessed by the relaxation time(Kelso et al. 1987) i.e., the number of cycles needed to recover to: (i) the line (informing on the task-goal outcome), (ii) the initial pattern after the perturbation (informing on the behaviour outcome). The recovery of the initial angle and coordination pattern was assessed by comparing each cycle after the perturbation to the average cycle (computed on ten cycles prior to the perturbation). When the cycle was in the confident interval of 95% (i.e., average cycle ± two standard deviations), it was not considered as perturbed. One way repeated measure ANOVA was conducted to detect speed effect on behavioural adaptation, with level of significance fixed at p<0.05.

Results

No statistical significant differences of towing force were observed between S60 (275 ± 88 N), S70 (251 ± 98 N), and S80 (248 ± 72 N). Significant effect of the flume water flow speed occurred (between S60-S70 / S80, p<0.05) when swimmers attempted to go back to the line after the perturbation: it took 3.3 ± 0.5 cycles at S60, 4.8 ± 1.2 cycles at S70 and 7.8 ± 3.2 cycles at S80. The recovery to the initial line was accompanied by significant increase in stroke rate before and during the perturbation (at S60, from 0.43 ± 0.11 Hz prior to perturbation to 0.72 ± 0.10 Hz during perturbation; at S70, from 0.49 ± 0.08 Hz prior to perturbation to 0.76 ± 0.07 Hz during perturbation; at S80, from 0.62 ± 0.11 Hz prior to perturbation to 0.79 ± 0.07 Hz during perturbation; p<0.05) but
not after the perturbation (0.45 ± 0.11 Hz at S60, 0.51 ± 0.09 Hz at S70, 0.66 ± 0.11 Hz at S80) suggesting that competitive swimmers were able to recover their initial stroke rate. The recovery to the initial line was also accompanied by significant change in behaviour outcome. In particular, when the standard deviations of the elbow-knee relative phase for the cycles following the perturbation were compared to the average cycle (calculated on ten cycles prior to the perturbation), numerous cycles were out of the confident interval (i.e., average cycle ± two standard deviation). Indeed, the elbow-knee coordination was perturbed during 3.5 ± 1.4 cycles at S60, 5.0 ± 1.1 cycles at S70 and 9.2 ± 6.7 cycles at S80, suggesting that the arm-leg coordination was perturbed during the same number of cycle than those required to come back to the initial line. These results suggest that there was a similar effect of the perturbation on the task-goal outcome and the behaviour outcome. However, it must be noted that large inter-individual variability was observed when the imposed swim speed of the flume was high (80% of maximal speed), with variation of relaxation time from 1 to 21 cycles to overcome the perturbation. The figures 1 and 2 provided an example of elbow-knee coordination modifications for one swimmer at 60% of his maximal speed.

![Figure 1](image1.png)

Note: The grey zone highlighted the perturbed cycles.

**Figure 1** Example of modification in elbow-knee relative phase when the perturbation is applied (dash line)

![Figure 2](image2.png)

Note: The perturbation was applied at the 15th cycle (white circle) and led to three perturbed cycles (black circle out of the confident interval). The perturbation ended when the cycles recovered in the confident interval.

**Figure 2** Example of cycles that are in or out the confident interval (dash line corresponds to average cycle ± two standard deviations) for elbow-knee relative phase

Logically, elbow and knee angles were also modified when the drag perturbation was applied. Interestingly, the number of cycle to adapt to the perturbation was not similar for elbow and knee
angles. Indeed, at S60, the knee angle was perturbed during 4.2 ± 1.7 cycles vs. 5.0 ± 2.5 cycles for elbow; at S70, the knee angle was perturbed during 6.3 ± 3.5 cycles vs. 3.8 ± 1.8 cycles for elbow; at S80, the knee angle was perturbed during 6.0 ± 4.3 cycles vs. 7.2 ± 4.8 cycles for elbow. Once again these results suggested large inter-individual variability (especially at S80) as some swimmers some swimmers revealed equivalent number of perturbed cycles between knee and elbow angles, but some others exhibited more knee cycle perturbed than elbow cycle, or more elbow cycle perturbed than knee cycle (as exemplified by the figures 3 to 6 for one swimmer at 60% of his maximal speed).

Note: The grey zone highlighted the perturbed cycles.

Figure 3 Example of modification in knee angle when the perturbation is applied (dash line)

Note: The perturbation led to three perturbed cycles (black circles out of the confident interval).

Figure 4 Example of cycles that are in or out the confident interval (dash line corresponds to average cycle ± two standard deviations) for knee angle
The previous results also highlighted that swimmers took significantly more time to come back to their initial elbow and knee angles and elbow-knee coordination pattern when the flume water speed was increased (p<0.05).

**Conclusion**

Competitive swimmers seemed to adapt very reactively to the perturbation, by generating acceleration of high magnitude to come back to their previous swim location. This adapting behaviour was accompanied by a much wider range of angular and coordination pattern at high speed than at slow speed. Moreover, large inter-individual variability suggested that some swimmers adapt their elbow-knee coordination by further changes in their knee movement while other swimmers mostly modified their elbow movement.

Adaptability to drag perturbation seems thus to be an interesting candidate to investigate behavioural skills in swimming at different speeds, and offers promising potential applications to test inter-limb coordination stability.

**References**


**Using inertial measurement unit for coordination pattern detection and recognition in breaststroke**

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**Abstract**

The aim of this study was to propose a method using inertial measurement units (IMU) for capturing elbow and knee angles in breaststroke in order to assess arm-leg coordination. Four IMUs were located on the forearm and the arm to assess elbow angle, and on the thigh and the leg to assess knee angle. The main challenge was the angle normalisation in order to correct the drift due to gyroscope measurement. To correct that drift, we proposed to compute wrapping lines around the angle signal, and to normalise the signal with the support of these reference lines. Even if the proposed method did not allow the definition of real joint positions, measurements allowed the definition of patterns of joint angles and the calculation of inter-limb coordination.

**Introduction**

Underwater, kinematic movement analysis is regularly conducted using 3D camera systems providing a high number of spatial-temporal parameters of behaviour. Even if the video analysis has proven his accuracy and usefulness in swimming, the use of such multi-camera systems is highly time consuming and involves many steps that may contribute to increase the error of measurement like calibration and digitising. Moreover, 3D multi-camera video device traditionally filmed a calibration frame that did not allow collection up to two cycles. Therefore one recent technological challenge was to design small, waterproof, light and wearable inertial measurement units (IMU) to collect all swimming cycles composing a 25m or 50m lap. This kind of device usually combines one or several accelerometers, gyroscopes and/or magnetometer to provide 3D analysis with different applications such as swimming strokes and stroke phases detection (Dadashi, Arami et al. 2013; Dadashi, Crettenand et al. 2013; Le Sage et al. 2011; Ohgi, Ichikawa, Homma & Miyaji 2003; Ohgi, Yasumura, Ichikawa & Miyaji 2000), swimming speed measurement (Stamm, Thiel, Burkett & James 2011), calculation of intra-cyclic speed variations of the sacrum (Dadashi, Crettenand, Millet & Aminian 2012), lap time and stroke rate measurement (Davey, Anderson & James 2008) or more broadly swimming lap monitoring (James, Burkett & Thiel 2011). Only few studies used IMU to assess limb angle and then inter-limb coordination (Komar, Hérault & Seifert 2013; Seifert, L’Hermette et al. 2011), which is a promising
way to analyse the status and role played by movement and coordination pattern variability during an event and under different constraints manipulation. From there, the aim of this study was to propose a method using IMU for capturing elbow and knee angles in breaststroke in order to assess inter-limb coordination.

**Method**

The participants were equipped with four IMUs (MotionLog which is an adapted version of MotionPod including a data logger with a waterproof design; Movea®, Grenoble, France) located on the forearm and the arm to assess elbow angle, and on the thigh and the leg to assess knee angle in breaststroke swimming. These IMUs were positioned on the left side of the swimmers: on the forearm (posterior surface of the proximal portion), the arm (posterior surface of the distal portion), the thigh (anterior surface of the distal portion) and the leg (anterior surface of the proximal portion), in order to place the sensors in direct contact with a bony part of the limb. The two limbs equipped with sensors wore strands of swimsuits in order to limit resistances due to the presence of the sensors. Prior to testing, the swimmers performed a vertical jump without flexing the leg to permit detection of simultaneous vertical acceleration in the four IMUs, for synchronisation purposes. Each IMU corresponded to a combination of a tri-axial accelerometer (+/-8G), tri-axial gyroscope (1600°/s) and a tri-axial magnetometer (MotionLog, Movea®, Grenoble, France), with 200Hz rate sampling. Data were recorded with North magnetic references and computed with MoveaLab software (Movea©, Grenoble, France). The angle is computed as an integration of the gyroscope measure. This integration makes the measurement highly prone to drift. To tackle the drift at low cost 8 steps have been undertaken on each sensor: 1) The vector norm was computed at each instant of the magnetometer sensor. This give us a periodic signal synchronised with the angle signal (from the gyroscope signal); 2) The low frequencies of that signal was captured with a butterworth low-pass filter then a segmentation was extracted from the resulting sinusoid; 3) The peak and the valley of the angle signal were computed for each cycle; 4) The peaks were filtered according to their prominence: a prominence that deviates more than 3 times for upper limbs or 2 times for lower limbs from the standard deviation is not involved in the further computation; 5) The same filtering is done on valleys; 6) A peak-line is computed from the remaining peaks with a spline regression; 7) In the same manner, a base-line is computed from the remaining valleys with a spline regression; 8) The angle is corrected and normalised by these wrapping lines. From there, angle key points of the cycle have been detected (confirmed by video footage inspection) to identify propulsion, glide and recovery. As previously done by Seifert et al. (Seifert, Leblanc, Herault et al. 2011), angle and angular velocity were normalised at an interval [-1, +1], then phase angle was computed for each oscillator in order to calculate continuous relative phase between elbow and knee.

**Results**

The main challenge was the angle normalisation in order to correct the drift due gyroscope measurement. To correct that drift, we proposed to compute wrapping lines around the angle signal, and to normalise the signal with the support of these reference lines. If we assume that the orientation of the magnetic field is constant during the recording, thus, the magnetometer data is then the only of the three kinds of data (gyroscope, accelerometer and magnetometer), which is absolute and non relative to past movement of the swimmer. For each sample of each sensor, the quadratic norm of the 3D magneto vector was computed. This signal is nearly a sinusoid with noise and a small amount of harmonics. In order to prevent those noise and harmonics to interfere with the segmentation, a 3-degree Butterworth low-pass filter with a cut frequency of 1.5 Hz was applied. Figures 1 and 2 show the raw norm signal and the filtered signal from arm and forearm sensors respectively.
The filtered signals from the arm and forearm were combined to form a segmentation indicator. This combination consisted in an addition when signals were in in-phase or a subtraction when they were in anti-phase. Thereafter, the segmentation consisted in detecting when the filtered-signal crossed the constant component (i.e., the mean of the signal) from the lower part to the upper part. From there, we get one detected point per cycle. Figure 3 shows the indicator on the segmentation for the elbow.
The next step was the ‘wrapping’ of the angle signal. The angle signal was computed as the integration of the difference of the gyroscopic signals of the arm and forearm sensors. If means of the gyroscopic signals were not null over a cycle, the integration introduced a drift that cumulated at each cycle. Figure 4 illustrates that drift on the elbow signal.

From each cycle, a single point was known from the segmentation. Between two consecutive segmentation points, the lowest point of the raw angle signal was computed and called as a ‘valley’. In the same way, the highest point of the raw angle signal between two consecutive segmentation points was computed and called as a ‘peak’. The prominence of each peak was computed; it consisted in the difference between the high of the peak and its neighbouring peaks. If the prominence was higher than three times the standard prominence of other peaks, that peak was considered an outlier and was not further used. The same filtering was applied to valley. From the remaining peaks, a peak line was computed based on a spline regression. In the same way, a valley line was computed based
on a spline regression from the remaining valleys. Those two lines surround the raw angle signal. Figure 5 illustrates the ‘wrapping’ of the elbow angle signal. Notes that the seventh valley was filtered out and wrapping lines started after the first cycle and stopped before the last cycle. This was due to the fact that valleys and peaks were computed in-between to segmentation points.

Figure 5  Example of raw elbow angle signal with peak and valley lines

The next step consisted to correct the angle. From the peak regression spline, we got a function of the time \( t \), \( \text{Peak}(t) \), that represents the peak line. From the valley regression spline, we got a function of the time \( t \), \( \text{Valley}(t) \), that represents the valley line. The corrected angle \( \text{CorrectedAngle}(t) \) was then computed from the raw signal \( \text{Angle}(t) \) through this formula:

\[
\text{CorrectedAngle}(t) = \frac{\text{Angle}(t)}{\text{Peak}(t) - \text{Valley}(t)}
\]

When the raw angle signal reached the peak line, the corrected angle was equal to 1. When the raw angle signal reached the valley line, the corrected angle was equal to 0. The result of this correction for the elbow angle was shown on figure 6.
Figure 6   Example of corrected elbow angle signal

The same process was applied to knee angle. This data processing did not allow getting absolute value of angle but only relative angle ($\theta_{\text{norm}}$) that was normalised between -1 and +1 (Hamill, Haddad & Mcdermott 2000), while cycle duration was also resampled in 100%. Figure 7 shows an example of superposed normalised cycles of elbow and knee angles, and angle key points detection, which is useful to interpret propulsion, glide and recovery durations. Key points are obtained by a piecewise linear regression: a cycle is modelled as a form of three consecutive segments, the intersection of the first two segments denotes the beginning of the plateau and the intersection of the last two segments denotes the end of the plateau. To initialise the regression, the first sample and the closest sample to upper left corner form the first segment, the closest sample to upper left corner and the closest sample to upper right corner form the second segment and finally the closest sample to upper right corner and the last sample form the third segment. In figure 7, the cycle was broken from the maximal knee flexion at cycle 1 to the maximal knee flexion at cycle 2. This knee flexion is the start of the leg propulsion. Then, the start and the end of the body glide were automatically detected.

Figure 7   Normalised cycles and elbow and knee angle key points detection: start of body glide (A) and end of body glide (B)
Angular velocities ($\omega_{\text{norm}}$) were also normalised in the interval [-1, +1]. Then, phase angles ($\phi_{\text{elbow}}$ and $\phi_{\text{knee}}$) in degrees were afterward calculated and corrected according to their quadrant (Hamill et al. 2000): $\phi = \arctan(\omega_{\text{norm}}/\theta_{\text{norm}})$. Finally, the continuous relative phase for a complete cycle was calculated as the difference between both phase angles (Hamill et al. 2000): $\phi_{\text{rel}} = \phi_{\text{elbow}} - \phi_{\text{knee}}$. Theoretically, two extreme modes of coordination are possible: in-phase ($\phi_{\text{rel}} = 0^\circ$) and anti-phase ($\phi_{\text{rel}} = 180^\circ$); however, following previous studies (Diedrich & Warren 1995; Seifert, Leblanc, Hérault, et al. 2011) on inter-limb coordination, a lag of ±30° was accepted to define the adopted coordination pattern. Therefore, an in-phase mode was assumed to occur when -30° < $\phi_{\text{rel}}$ > 30°, while an anti-phase mode was defined by -180° < $\phi_{\text{rel}}$ > -150° and 150° < $\phi_{\text{rel}}$ > 180°.

**Conclusions**

Even if the proposed method did not allow the definition of real joint positions, measurements allowed the definition of patterns of joint angles and the calculation of inter-limb coordination. This work opens new perspectives in the use of IMU especially for race analysis where cycle-to-cycle assessment is promising. In addition, this method allows a quick data processing and therefore rapid feedback to the swimmer about the assessment.

**References**


A multi-analysis of performance in 13- to 15-year-old swimmers: a pilot study

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Keywords: young swimmers, front crawl, kinematics, motor control

Introduction

Swimming performance is a multi-factorial phenomenon depending on several factors such as energetics, biomechanics, hydrodynamics, anthropometrics and strength parameters (Poujade et al. 2002; Barbosa et al. 2009). Considering that heavy training loads start at relatively young ages, it seems important to assess which parameters best predict swimming performance.

In a longitudinal study, Tella et al. (2002) reported that the improvement observed in young swimmers performance results from an increase in stroke length (SL), which reflects, in part, the increase of anthropometrical characteristics (arm span, height and hands and feet length). Similarly, Chatard et al. (1990) stated that performance is related to passive drag, which depends on anthropometric factors. More recently, in a swimming performance’s multivariate analysis, it was found that higher height and arm span, characterised the best male swimmers (Saavedra et al. 2010). Other studies found similar results (e.g. Lätt et al. 2010; Geladas et al. 2005), allowing researchers to conclude that usually higher height and arm span benefits swimming efficiency (i.e. higher SL) (Saavedra et al. 2010) and a better glide (Geladas et al. 2005; Toussaint and Hollander 1994). However, this larger SL could be also related to a hyperflexibility presented by swimmers, which benefit the glide and create less resistance (they could streamline their body to a greater extent). This contributes to a more laminar and less turbulent flow around the pressure points, such as the shoulder, hip, knee, ankle, where most of the changes in body shape occur (Chatard et al. 1990).

Many sports depend mainly upon muscular strength and aerobic enhancement especially at a competitive level (Leveritt et al. 2000), as in swimming. In fact, studies showed positive effect of dry-land upper limb strength training, varying the gains in sprint performance between 1.3 and 4.4% (Strass 1988; Costill 1999). Regarding young swimmers, it was noticed that the significant increase in velocity between 12 to 14 years old is coincided with a significant increase in the mean force production (Taylor et al. 2003). Moreover, strength training could allow the enhancement in coordinative profile, helping the swimmer to improve his/her technique (Maglischo 2003). In fact, when competitive young swimmers are involved in strength training, to take full benefit of an increase in muscle strength, coordination needs to be adapted (Newton et al. 2002). The swimmer has to modify the control of the neuromuscular system, commonly referred as coordination, timing or technique, to actually produce an increased in-water performance (Faigenbaum 2000). Unfortunately, results that try to support this idea remain inconclusive (Girold et al. 2007; Aspenes et al. 2009). Nevertheless, it was found positive associations between in-water and dry-land tests (Morouço et al. 2011a), as well as strong relationship between mean absolute force and the time at 50 m for the four swimming techniques (Morouço et al. 2011b).

The aim of this study was to determine which parameters are predominant to achieve better performances in age group swimmers. It was hypothesised that faster swimmers are taller and
achieve higher values of mean ($F_{\text{mean}}$) and maximal force ($F_{\text{max}}$). Moreover, it was hypothesised that faster swimmers present a more continuous arm coordination movement pattern, reflected through higher index of coordination (IdC) values.

**Methods**

**Participants**

Eighteen young female swimmers were divided in two groups considering their performance level. The local Ethics Committee approved the experimental procedures, and the swimmer’s parents signed a consent form in which the protocol was described. Their main characteristics and swimming performance level, assessed as best scores in the FINA table, are presented in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Main characteristics of the two groups of swimmers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>Years of Practice</td>
</tr>
<tr>
<td>Group 1</td>
<td>14.00 (0.76)</td>
</tr>
<tr>
<td>Group 2</td>
<td>13.40 (0.52)</td>
</tr>
</tbody>
</table>

*Statistically significant differences between groups (P < 0.05).

**Experimental procedures**

The tests were performed in a 25 m indoor pool. A warm-up of low to moderate swimming intensity was conducted. Each swimmer performed four different tasks: (i) an anthropometrical and flexibility evaluations; (ii) 25 m front crawl at 50 m race pace; (iii) 30 s tethered swimming maximal effort and (iv) ten incremental velocity bouts on the MAD-system. For the kinematic evaluation, swimmers were videotaped in the sagittal and frontal plane using two underwater video cameras (Sony® DCR-HC42E, 1/250 digital shutter, Nagoya, Japan), placed inside a sealed housing (SPK – HCB waterproof box, Tokyo, Japan), recorded two complete underwater upper limb cycles. A bi-dimensional image calibration structure (6.30m$^2$, and 13 calibration points) was used to transform the virtual coordinates into the real ones. Kinematical analysis was performed using APASystem software (Ariel Dynamics, San Diego, USA), digitising manually and frame by frame (at 50 Hz) the anatomical landmarks corresponding to the skin markers. The hip (femoral condyle) and, on both sides of the body, the distal end of the middle finger, the wrist, the elbow, the shoulder and the ankle were digitised.

**Anthropometric and flexibility measurement**

The anthropometric measurements were taken according to standardised procedures (Saavedra et al. 2010), including body dimensions as height and arm span, foot and hand length. Regarding flexibility, the shoulder joint maximal flexion and extension was analyzed, using a goniometer.

**Biomechanical parameters**

To perform the 25 m front crawl at 50 m race pace, swimmers started in the water and swam alone, without the pressure of opponents, to reduce the drafting or pacing effects (Barbosa et al. 2010). Afterwards, swimmers were informed of their performance time, which was expected to be within ± 2.5% of the targeted race speed; when the time was unexpected, the subject repeated the trial after a 30 min interval.

Swimming velocity was assessed through the ratio of the displacement of the hip in a stroke cycle to its total duration. SL was determined by the horizontal distance travelled by the hip during a stroke cycle, and stroke rate (SR) as the number of stroke cycles performed per min. The stroke index (SI) was computed by the product of velocity and SL. The SL ration was also calculated. The IdC was also measured through the images recorded, by measuring the time between the beginning of propulsion of the first right arm stroke and the end of propulsion of the first left arm stroke, and between the beginning of propulsion of the second left arm stroke and the end of propulsion of the first right arm.
stroke (Chollet et al. 2000). IdC was calculated based on the division of the arm actions in four phases: (i) entry/catch, corresponding to the time since the entry of the hand in the water until it starts to make the backward movement; (ii) pull, from the end of the previous action until achieving vertical alignment of the shoulder (first propulsive phase); (iii) push, from the end of the previous action to the exit the hand of the water (second propulsive phase) and (iv) recovery, which is the time from the exit of the hand until its new entry. The IdC and each stroke phase were expressed as the percentage of the duration of a complete arm stroke; the sum of the pull and the push phases, and of the catch and the recovery phases, indicate the duration of the propulsive and non-propulsive phases, respectively.

**Tethered swimming**

Each swimmer performed 30 s front crawl at maximal intensity in tethered swimming. The subjects wore a belt attached to a steel cable with 5 m length (sufficiently stiff that its elasticity could be neglected), which was connected to a load-cell. The force signal was acquired by an A/D converter (BIOPAC System, Inc., Goleta, CA, USA) at a sample rate of 500Hz and filtered with a low pass digital filter with a cut-off frequency of 10Hz. Preceding the starting signal, swimmers adopted a horizontal position with the cable fully extended, starting the data collection only after the first stroke cycle was completed. This procedure was used to avoid the inertial effect of the cable extension usually observed immediately before or during the first arm action (Morouço et al. 2011b). The test ending was set through an acoustic signal. Swimmers were told to choose the breathing patterns that normally apply in the 50 m front crawl event. The graphic force/time was registered and analyzed to obtain the values of F_{mean} (mean value of force within 30 s) F_{max} (value obtained in the first 5 s), minimum force (F_{min} – mean value over the last 5 s). Through these values the fatigue index (FI) was calculated: fatigue index = [(F_{max} − F_{min}) / F_{max}] * 100 (Rohrs & Stager 1991; Morouço et al. 2012).

**MAD-System**

To measure drag at maximal velocity, swimmers performed ten incremental velocity bouts in MAD-system. This apparatus require the swimmer to push-off sixteen fixed pads attached to a 23 m rod, which was fixed 0.8 m below water surface, and had a standard distance of 1.35 m between each pad (Toussaint et al. 2004; Ribeiro et al. 2013). The rod was instrumented with a force transducer allowing measurement of push-off force from each pad. The force signal was acquired by an A/D converter (BIOPAC System, Inc., Goleta, CA, USA) at a sample rate of 500Hz and filtered with a low pass digital filter with a cut-off frequency of 10Hz. Assuming a constant swimming velocity, the mean force equals to mean drag force and, hence, the 10 velocity/force ratio data were least square fitted according to Equation 1:

\[ D = A \cdot v^n \]  

where D is active drag force, A and n are parameters of the power function and v represents the swimming velocity. For each subject A and n were estimated using Equation 1 (Matlab version R2012a, Mathworks, Inc., Natick, MA, USA) with Levenberg-Marquardt algorithm (Toussaint et al. 2004). Swimmers only used their arms, their legs were supported and fixed by a pullbuoy. The first and the last push off are not included in the analysis in order to eliminate the influence of the push off from the wall and the deceleration of the swimmer at the end of the length.

**Statistics**

Data were tested for normality of distribution and the statistical analysis performed was based on exploratory data analysis. Mean and SD were calculated for all measured parameters. One-way ANOVA was performed to compare groups (p < 0.05). The effect size of each variable was also calculated.
**Results**

The mean and SD values regarding anthropometric, flexibility of shoulder joint, biomechanical, strength and active drag parameters are described in Table 2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>G1 (n = 8)</th>
<th>G2 (n = 10)</th>
<th>p-value</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthropometric</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>160.6 (5.1)</td>
<td>161.1 (8.1)</td>
<td>0.89</td>
<td>0.13</td>
</tr>
<tr>
<td>Arm span (cm)</td>
<td>162.50 (4.81)</td>
<td>159.62 (9.70)</td>
<td>0.46</td>
<td>3.53</td>
</tr>
<tr>
<td>Foot length (cm)</td>
<td>22.83 (1.28)</td>
<td>22.20 (0.98)</td>
<td>0.26</td>
<td>7.94</td>
</tr>
<tr>
<td>Hand length (cm)</td>
<td>16.95 (0.46)</td>
<td>17.40 (1.43)</td>
<td>0.41</td>
<td>4.34</td>
</tr>
<tr>
<td>Flexibility</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal right shoulder flexion (º)</td>
<td>195.00 (6.55)</td>
<td>187.40 (3.50)</td>
<td>0.006</td>
<td>38.48</td>
</tr>
<tr>
<td>Maximal left shoulder flexion (º)</td>
<td>191.25 (2.31)</td>
<td>183.00 (4.22)</td>
<td>&lt;0.001</td>
<td>60.50</td>
</tr>
<tr>
<td>Maximal right shoulder extension (º)</td>
<td>67.50 (4.63)</td>
<td>68.00 (10.33)</td>
<td>0.90</td>
<td>0.10</td>
</tr>
<tr>
<td>Maximal left shoulder extension (º)</td>
<td>75.00 (5.35)</td>
<td>69.00 (8.43)</td>
<td>0.10</td>
<td>19.05</td>
</tr>
<tr>
<td>Biomechanical</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swimming velocity (m/s)</td>
<td>1.68 (0.02)</td>
<td>1.58 (0.04)</td>
<td>&lt;0.001</td>
<td>73.33</td>
</tr>
<tr>
<td>SL (m)</td>
<td>1.99 (0.15)</td>
<td>1.83 (0.18)</td>
<td>0.06</td>
<td>20.46</td>
</tr>
<tr>
<td>SR (cycles/min)</td>
<td>50.89 (3.81)</td>
<td>52.19 (4.17)</td>
<td>0.51</td>
<td>2.82</td>
</tr>
<tr>
<td>SI (m².s⁻¹)</td>
<td>3.34 (0.23)</td>
<td>2.89 (0.36)</td>
<td>0.007</td>
<td>37.56</td>
</tr>
<tr>
<td>IdC (%)</td>
<td>-8.60 (1.44)</td>
<td>-5.53 (3.15)</td>
<td>0.02</td>
<td>28.76</td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Force (N)</td>
<td>169.6±75.4</td>
<td>119.0±14.4</td>
<td>0.05</td>
<td>21.48</td>
</tr>
<tr>
<td>Maximal Force (N)</td>
<td>178.7±73.5</td>
<td>127.0±14.6</td>
<td>0.04</td>
<td>22.99</td>
</tr>
<tr>
<td>Fatigue Index (N)</td>
<td>11.42 (5.08)</td>
<td>11.99 (5.55)</td>
<td>0.98</td>
<td>0.003</td>
</tr>
<tr>
<td>MAD-System</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drag at maximal velocity (N)</td>
<td>59.00 (20.60)</td>
<td>50.70 (11.50)</td>
<td>0.29</td>
<td>6.92</td>
</tr>
</tbody>
</table>

No differences were found in anthropometric characteristics, active drag and FI between groups. G1 showed higher shoulder flexion, SL, SI, F\textsubscript{mean} and F\textsubscript{max} than G2. Although both groups presented catch-up coordination mode, IdC was lower in G1. Regarding effect size, it is possible to observe that swimming velocity is the main parameter that distinguishes the two groups. However, the ability to obtain a wide range of left shoulder flexion, seems to play an important role. Probably associated with these two last parameters, appears the maximal right shoulder flexion and SI. Conversely, FI, maximal right shoulder extension and height were the parameters less important to distinguish these two groups of swimmers.

**Discussion**

The aim of this study was to determine which parameters are predominant to achieve better performances in age group swimmers. The higher SL, SI, F\textsubscript{mean}, F\textsubscript{max}, shoulder flexion, better hydrodynamic profile, but lower IdC values, were the most important parameters. As both groups have similar anthropometrical characteristics, the higher velocity attained by G1 can be explained by a better technique (particularly the higher SL and SI values). Moreover, strength characteristics also seem to play an important role, since faster swimmers achieved higher values of F\textsubscript{mean} and F\textsubscript{max}, as hypothesised. The second hypothesis was not confirmed, as faster swimmers presented a more negative IdC than slower swimmers, i.e. they presented a higher lag time between propulsive arm phases. However, both groups adopted catch-up coordination mode.
The better swimming technique showed by G1 was confirmed through a higher SL values presented by this group, as both G1 and G2 presented similar anthropometric values. Moreover, G1 also achieved higher SI values, which is explained by its dependence of velocity and SL. In fact, SI is an index that represents swimming technical efficiency, since higher values denote that the swimmer covers a given distance with fastest time and with less number of strokes. Regarding young swimmers, Lätt et al. (2010) have already reported the importance of biomechanical parameters, showing that these parameters may explain 90.3% of the variance in 100-m swimming performance. Moreover, these results could be influenced by flexibility, since G1 showed greater range of shoulder flexion, which could be expressed in the higher SL values observed in this group. Thus, with a streamlined body, these swimmers could express a better glide, creating less resistance, and consequently, a better hydrodynamic profile. The catch-up mode adopted by young swimmers was in opposition to what was hypothesised, faster swimmers showed lower IdC values, representing a less continuous arm coordination movement pattern. This result contrast to those obtained by adult elite swimmers (e.g. Chollet et al. 2000; Seifert et al. 2007) and with a study conducted on two groups (pubertal and post-pubertal) of young swimmers that presented different velocities (Silva et al. 2012). The reason for these results could be related to the higher strength values applied by G1 during the propulsive arm phases, i.e. as G1 presented higher strength values (F_{mean} of 169.6±75.4 vs. 119.0±14.4 and F_{max} of 178.7±73.5 vs. 127.0±14.6 for G1 and G2, respectively), their movement could be faster and more effective. Indeed, Sozański (1999) stated that the age between 11 to 14 years old are characterised as a period of versatility, for mastering the technique and to prepare for a progressive workout.

An optimal level of strength and power is necessary for successful performance in many sports, and swimming is no exception (Newton et al. 2002). Indeed, faster swimmers presented higher values of F_{max} and also F_{mean}, suggesting that force is very important for maximal efforts. In addition, Fi was similar for both groups supporting the hypothesis that propulsive forces were more efficiently applied by G1. In fact, it was reported that strength training improves swimming performance (Toussaint et al. 1990; Girold et al. 2007), which result in an increase in SL (Toussaint et al. 1990), a reduction in SR (Girold et al. 2007) and in an increase in tethered swimming force (Toussaint et al. 1990; Girold et al. 2007). These results could also influenced drag, as in a longitudinal study (2.5 year period of growth) with young swimmers, Toussaint et al. (1990) showed that, with no differences in drag values, the 14% improvement of the swimming performance in the 100 m time performance were related to a higher maximal force (34%), velocity (12%), and power (49%) measured on the MAD-system. Indeed, in the present study, even though G1 attained higher velocity, similar drag values were presented by the groups, which suggests a better hydrodynamic profile of G1.

As a conclusion, higher performances in young female swimmers, are linked to a greater SL, SI, F_{mean}, F_{max}, shoulder flexion, better hydrodynamic profile, but also to lower IdC values.

**Acknowledgments**

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**References**


Muscle activation during swimming exergame

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Keywords: biomechanics, muscle activation, virtual swimming, surface electromyography

Abstract

Swimming exergames may provide low-cost opportunities for teaching and practicing real swimming. The purpose of this study was to characterise the muscle activation during a swimming exergame. Ten healthy subjects played four swimming techniques using ‘Michael Phelps: Push the Limit’ exergame by standing in front of Xbox360 and Kinect. Muscle activation for Biceps Brachialis (Bi), Triceps Brachialis (Tri), Latissimus Dorsi (LD), Upper Trapezius (UT) and Erector Spinae (ES) was recorded on dominant upper limb using a wireless EMG Trigno system (Delsys Inc, USA) at sampling rate of 2000 Hz, and was normalised to the maximal voluntary isometric contraction. EMG recordings were divided into a low intensity phase and a second phase of fast swimming. Both phases were evaluated in terms of EMG morphology (average peak value). Preliminary results show high contributions of UT. Particularly high activation values were obtained for back crawl, where more expressive shoulder flexion is required. Lower contributions of other muscles might be related to lack of sufficient mechanical resistance. Prevalence of the activity of the Tri relatively to the Bi was also observed, as expected, considering the final acceleration of the lower part of the arm in all swimming techniques. Due to great activity of UT, proper warm up and the use of strategies to transfer the muscle activity are advisable. More results of this ongoing project will be available in the future.

Introduction

Video game playing is increasing among youth (Lenhart et al. 2008) with the gaming experience being changed significantly in the last years. As they are part of screen-based activities which account for players’ sedentary time, high exposures to video games has raised physiological and psychological concerns (Roberts et al. 2004). This has led to design a new type of video game (tagged as active video games or Exergames) in which the players can interact with the game physically and in a more natural way, hypothetically increasing physical activity levels regarding other screen-based activities. These gaming platforms use accelerometers, infra-red depth sensors, and cameras to detect player’s movements to simulate on-screen game play. Using Kinect (see Leyvand et al. (2011) for details), players can interact with the game without holding anything, as it can detect full body joint segment (Zhang 2012).

According to the Entertainment Software Association (2011), sports video games are the second ‘action’ genre in terms of popularity. Hayes and Silberman (2007) suggested that exergames should be of interest in physical education to increase motivation and facilitate motor skill learning. However, detailed evaluation is needed to ‘prove’ the benefits of sport exergames. If it shows similar movement patterns as real sports, they can potentially be a low-cost and effective tool in teaching and training sports.

Understanding muscular activation while playing exergames allows safe playing for both players and their peers. As most of the exergames consist of repetitive tasks, excessive playing of exergames have led to injuries and medical doctors introduced Wii shoulder (Cowley & Minnaar 2008), Wiiitis (Bonis 2007; Nett et al. 2008) and X-boxitis conditions after playing too much active video games. Risks
caused by the game may be controlled by monitoring muscle activation during playing, which is especially important when the games are so engaging that the players would not be completely aware of their body and the time they spend on playing. Moreover, as exergames might be a good tool for unsupervised and self-directed rehabilitation, understanding muscular involvement is also necessary for considering prescription and for effective and secure training sessions (Tanaka et al. 2012).

The design of games and different controllers may affect posture and muscle loading (Lui et al. 2011). As enjoyment and other factors may contribute to high exposure of people to these games, a detailed biomechanical analysis during game design may prevent potential musculoskeletal symptoms. In order to make video games more realistic, ‘Naïve Physics’ which is human perception of knowledge about the physical world, was introduced by Jacob et al. (2007). Applying the same physical principles of real sports while designing exergames may allow a more meaningful game play. This is important when participating in real sports happens before playing the exergame (Mueller et al. 2009).

Characterising exergames is helpful in designing harder levels while preventing a sudden occurrence of fatigue.

It seems that sport exergames have the potential to be used within the physical education settings. However, this needs to be supported by empirical evidence. To date, very few studies analyzed and compared muscular activity in exergames. Thus, to build a muscular activity profile for exergames, the purpose of this study was to provide the level of muscle activation in a swimming exergame.

**Methods**

Ten healthy male subjects who had no physical injuries (age 24.1±3.3 yr; weight 71.7±6.1 Kg; height 175.1±7.2 cm) played bouts of a swimming exergame. The pilot study was conducted at the University of Porto Biomechanics Laboratory (LABIOMEP). Participants were recruited online, face-to-face and through flyers. Informed consent forms were signed by participants prior to testing and procedures were approved by the local ethics committee. Anthropometric measures were taken and the participants were familiarised with the equipment and the procedure. As part of the game, they watched a brief instructional video in which playing with the game was demonstrated.

EMG sensors were placed on the dominant upper limb/side of players (Figure 1B). The muscles of interest for this study were the Biceps Brachialis (Bi), Triceps Brachialis (Tri), Latissimus Dorsi (LD), Upper Trapezius (UT) and Erector Spinae (ES), which are frequently used in swimming (Mcleod 2010). Erector Spinae was considered as players had to lean forward in the beginning and at the end of the game play. Electrodes were placed according to SENIAM recommendations (Freriks et al. 1999). Skin Preparation involved cleaning, dry shaving, rubbing with alcohol-soaked pads and then allowing alcohol to vaporise. Muscle activation was recorded using a Trigno Wireless EMG System (Delsys Inc., USA) at a sampling rate of 2000 Hz, for both MVIC and Exergame trials.

The Biodex System 4 (Biodex Medical Systems, Shirley, NY) was used to obtain MVICs and was calibrated before each use according to the manufacturer’s instructions. Three MVIC attempts for each muscle were obtained, Each one lasted 10 s (2 seconds rest in the beginning, 5 seconds of muscle contraction and 3 more seconds to reduce gradually ending with a new isoelectric line) with one minute rest between attempts. The MVIC values were chosen from the highest value of the three attempts and used to normalise the trial data. Verbal encouragement was provided throughout the MVIC attempts. Positioning of Biodex for Bi and Tri were performed according to Gennisson et al. (2005) and Lategan & Kruger (2005), respectively. For UT and LD, MVICs were performed according to Hong et al. (2012) and for ES, we followed Moreau et al. (2001).

The exercise task was a swimming exergame designed for Xbox gaming platform. The software used was ‘Michael Phelps: Push the Limit’ (505 Games, Milan, Italy), a game that offers different swimming techniques and uses Kinect (Figure 1A), which connects to the Xbox via a USB cable, allowing users to interact physically with the game. A promotional video is available here: http://goo.gl/zPvHZL. Four
swimming techniques mimicking the four competitive swimming techniques were played randomly during this study. Each event consisted of 100-meters of virtual swimming. Subjects had to stand in front of the Kinect sensor, bent forward and, as soon as they saw the ‘Go!’ command, they had to return back to normal playing position: slightly bent forward, with shoulder partially flexed, and upper limbs in front of the body (shoulder extension) (Figure 1C). After that, they had to swing their arms according to the technique to move the avatar in the game (100 meters front crawl swimming). At the end of the event, they had to drop both hands and then raise one of them to finish the race (corresponding to virtually touching the end of the lane). To prevent the player from swimming too fast or too slow, there is a spectrum on the screen with a blue zone in the middle which indicates if the cycle frequency is at the moderate level. At the middle of the second lap, there is a possibility to swim as fast as possible called ‘Push the Limit’. If players swim with a constant speed, they could reserve energy on a so called energy bar to exert more in the push the limit phase.

Figure 1  Game screenshot (A), positioning of sensors (B) and participants as they play (C)

EMG data processing was performed using EMG Works Analysis 4.0 (Delsys Inc, USA), and it included signal filtering between 20-450 Hz, full-wave rectification and Root Mean Square (RMS) envelope calculation using a 150 ms window. This process was performed for both the MVIC and the trial data. To determine whether there is a statistically significant mean difference between the five muscles in normal and fast mode, a paired t-test was run on each technique ($p < 0.05$).

**Results**

Table 1 presents EMG RMS mean±SD data expressed as a percentage of MVIC, obtained during ‘normal’ and ‘fast’ swimming from the selected muscles. The paired t-test showed significant change between normal and fast swimming in breaststroke, butterfly and crawl ($t(4) = -4.27, p = 0.01$; $t(4) = -3.49, p = 0.02$; $t(4) = -3.80, p = 0.01$, respectively). There was not a significant change in back crawl between the muscles from normal to fast swimming phases ($t(4) = -2.67, p = 0.06$).

<table>
<thead>
<tr>
<th></th>
<th>Bi</th>
<th>Tri</th>
<th>LD</th>
<th>UT</th>
<th>ES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Back Crawl</strong></td>
<td>Normal</td>
<td>4.9±2.4</td>
<td>17.0±16.2</td>
<td>15.4±10.4</td>
<td>47.0±15.5</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>8.2±5.0</td>
<td>23.7±22.1</td>
<td>21.7±18.1</td>
<td>69.3±18.6</td>
</tr>
<tr>
<td><strong>Breaststroke</strong></td>
<td>Normal</td>
<td>10.0±5.5</td>
<td>19.0±18.2</td>
<td>11.1±6.7</td>
<td>29.0±19.3</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>18.3±7.2</td>
<td>28.8±31.7</td>
<td>20.6±12.4</td>
<td>46.1±40.8</td>
</tr>
<tr>
<td><strong>Butterfly</strong></td>
<td>Normal</td>
<td>5.6±2.0</td>
<td>23.4±21.3</td>
<td>24.4±32.7</td>
<td>43.8±19.0</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>9.7±3.9</td>
<td>33.1±26.2</td>
<td>50.8±66.8</td>
<td>65.4±34.4</td>
</tr>
<tr>
<td><strong>Crawl</strong></td>
<td>Normal</td>
<td>8.2±3.1</td>
<td>16.2±15.6</td>
<td>11.8±7.6</td>
<td>39.7±22.5</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>15.2±4.8</td>
<td>23.0±24.6</td>
<td>22.9±14.9</td>
<td>63.7±31.5</td>
</tr>
</tbody>
</table>

*: significant changes were observed between normal and fast swimming in muscle groups; Bi = Biceps Brachii; Tri = Triceps Brachii; LD = Latissimus Dorsi; UT = Upper Trapezius; ES = Erector Spinae

Figure 2 presents a visual time sequencing of muscle activation.
Discussion

Preliminary results show high contributions of UT in all techniques. This is probably because players always have to hold their upper limbs up/front during playing (shoulder flexed). Particularly high activation values were obtained for back crawl, where more expressive shoulder flexion/rotation is required. In addition, players tended to face the screen and avoided rotation their bodies, which may justify why there were not any significant changes between normal and fast swimming as players had to exert a lot during both phases.

The activation pattern for Bi and Tri were similar in crawl, back crawl and butterfly. After the elbow reaches a point of maximal flexion (which occurs when the arms are down), Tri assists the arms to be lifted (starting push phase) progressing into an extended position. Interesting to note is the persistent pattern of co-contraction of this pare of antagonists, probably for elbow stabilisation. Shortly after recruitment of the Tri, UT would be activated again holding the arms all the way through the push and recovery phase.

In crawl, the activation of LD is in accordance with Bi. As the arms are down, the activation of LD finishes leading to recruitment of Tri. The activation pattern of LD and ES fades away as players switch from playing emotionally (really completing the cycles) to technically (in a way that much of the work is being done by gravity). As they start the fast swimming phase, these patterns become visible again showing that those muscles are helping extending the upper limbs again to complete the cycles. As activation of ES serves a key in coordination of the body roll, lack of activation of this muscle shows that players tended to face the television and do the movement without rotating the body (the same situation occurs in butterfly). This happens as the players wanted to synchronise their cycle frequency with the visual feedback on the screen. In the fast phase of swimming, where no visual feedback was given, players tended to rotate their body (activation of ES) along with other muscles.

In breaststroke, the activity pattern of Tri and UT were similar. Tri extends the arms completely to the front and meanwhile UT is bearing the weight of upper limbs. UT remains active even in the so called recovery phase as it is still holding the upper limbs. Due to great activity of UT, proper warm up and the use of strategies to transfer the muscle activity is advisable. Lower contributions of other muscles are most probably related to lack of sufficient mechanical resistance of air. This suggests that increasing mechanical resistance to arms’ movements may be a solution to implement the game playing conditions. Prevalence of the activity of the Tri relatively to the Bi was observed, as expected considering the final acceleration of the lower arm in all swimming techniques.
The empirical evidence that supports the effectiveness of sport exergames systems in teaching and training real sports is limited, since no study characterised sport exergames to provide an insight on how real they are when played. This study aims to create a muscle activation profile during playing a sport exergame. Although this swimming exergame is mostly different than real swimming (e.g. body position and forces applied to the body), swimming technique needs to be the same for a meaningful experience. More results of this ongoing project will be available in the future.

References


Evaluation of motion on underwater monofin swimming for novice

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Keywords: finswimming, monofin, apnea, novice, sine wave

This study aims to evaluate the relationships between horizontal velocity, kick rate, kick length, and the range of motion of each body part in apnea finswimming. Research was conducted on 81 male and 26 female high-school swimmers without monofin swimming experience. Each subject swam at their maximum performance during the test. Measurements for motion analysis were taken for the wrists, elbows, shoulders, hips, knees, ankles and the tip of the monofin. We used the vertical displacement of each body part over time to approximate a sine wave (z=a1*sin (b1*t+c1) +d1*t+e1).

Using these figures, we observed the following three points.

1) For male subjects, no correlations were observed between horizontal velocity and the length of amplitudes of the wrists, elbows, shoulders, hips and knees. For females, no correlations were found between horizontal velocity and the length of amplitudes of the shoulders and hips. 2) There was a negative correlation between kick rate and amplitudes for both males and females (Elbow r = -.660, p<.01) 3) There was a significant positive correlation between kick length and the amplitudes of the lower limbs. (Males: Ankle r=.888 p<.01, Females: Ankle r=.863 p<.01)

Introduction

Finswimming refers to ‘progression with monofin or with two fins either on the surface or underwater, by means of the swimmers’ muscular force only and without use of any mechanism’, (World Underwater Federation 2013a). Finswimming encompasses the following four disciplines. Apnea is underwater finswimming with a large monofin resembling the tailfin of a dolphin. Immersion swimming involves diving with an oxygen tank. Surface swimming is swimming on the surface of water with snorkeling gear, and bifin swimming is swimming crawl style with two fins, as used for diving (World Underwater Federation 2013b). The world record for 50-meter apnea finswimming is 13.89 seconds, which is 7.02 seconds faster than the world swimming record 20.91 seconds (World Underwater Federation 2013c; International Swimming Federation 2013b). Finswimming enables athletes to swim at a high speed that cannot be experienced in regular swimming, but it is not as widespread as regular swimming. In order to promote the spread and development of finswimming, it is necessary to research common points of failure observed in inexperienced fin swimmers, and establish better instruction methodologies for beginners.

The research studies on finswimming (Rejman & Ochmann 2007; Rejman & Ochmann 2009; Nicolas et al. 2010) include kinematics studies, (Nicolas et al. 2007) physiological studies, (Zamparo et al. 2006; Boitel et al. 2010) and more. However, there are few previous studies focusing on inexperienced monofin swimmers. The study of Gautier et al. (2004) compared swimmers with low training levels to advanced swimmers, and found that the amplitude of the motion of the upper limbs was large, but the motion of the lower limbs was small. It is clear that the amplitude of each body part is an important factor in swimming speed, but despite the fins used in finswimming, the amplitude of the fin was not mentioned. We deemed it necessary to conduct an analysis including the motion of the fin. The previous studies showed that the relationship between amplitude and swimming speed differs for each body part, but the fin was not discussed. If any correlation between swimming speed and some aspect of a swimmer’s motion is found, swimmers should receive more instruction in control of that motion. For parts of the motion that do not affect swimming speed, instruction in controlling that movement becomes lower priority. Thus, analyzing the relationships between the motion of each body part and swimming speed enables instructors to provide better guidance regarding form and technique for inexperienced monofin swimmers.
Rejman (2013) reported a correlation among propellant speed, kick rate, (number of kicks per second, Hz) kick length, (forward distance produced by one kick, m / kick) and amplitude. It is believed that finswimming enables swimmers to increase the amplitude of each body part. It also increases kick length and allows a faster kick rate, which improves swimming speed. However, Nicolas et al. (2007) stated, 'The Strouhal number is a trade-off between amplitude and frequency that generates a forward velocity.' This study showed that swimmers with higher kick rates and smaller amplitudes of motion, or slower kick rates with larger amplitudes, had improved swimming speeds. Unfortunately, the subjects were all international level swimmers, and no consideration was made of beginner finswimming competitions. Generally, inexperienced fin swimmers are unskilled at apnea finswimming, so they tend to have both small amplitudes and slower kick rates. In such cases, one might observe no negative correlations between kick rate and the amplitude of each body part, and thus not observe the 'trade-off', or correlation, described above. If there is no observable trade-off, it is possible to improve both the amplitude and kick rate for beginners. On the other hand, no studies about the relationship between amplitude and kick length had been published at the time of this writing, and the relationship between amplitude, kick rate, and kick length has not been verified. Clarifying these relationships would allow educators to find ways to enhance the swimming speeds of inexperienced monofin swimmers.

In this study, we had high-school swimmers without monofin swimming experience attempt apnea finswimming, and evaluated the relationships between the amplitude of each body part and swimming speed, kick rate, and kick length.

**Methods**

This study protocol was approved by the Kyoto Institute of Technology Ethics Committee for Scientific Research Involving Human Subjects. The subjects were 107 high-school swimmers without monofin swimming experience, comprised of 81 males (height: 170.1 (5.5) cm, weight: 58.1 (5.6) kg, FINA Points: 412.5 (107.2) points) and 26 females (height: 159.8 (3.3) cm, weight: 50.0 (4.9) kg, FINA Points: 479.9 (108.5) points). The FINA Points system assigns points to swimming performances to allow comparison across different events, and helps to distinguish the levels of each category (International Swimming Federation 2013a). Prior to the experiment, all participants carried out warm-up exercises and equipped a monofin according to our instructions. As a safety precaution, we instructed swimmers on how to move in the water without swimming. We then had them swim 25 meters apnea at their maximum performance during the test. Images were taken from the swimmer's right side using an underwater video camera (SONY, HXR-MC1, 59.94 Hz). The video camera was set on a tripod to fix the angle of view, and recorded from between 7 and 11 meters from the right side of the participants. After recording, the videos were transferred to PC and analyzed using motion analysis software, (Frame DIAS-IV, DKH Co.,). The horizontal direction of the image was defined as the Y-axis and the vertical direction was defined as the Z-axis, with the coordinate system at rest. Apnea swimming includes none of the rolling motion of crawling, and performance was measured in a two-dimensional motion plane. The targets of our analysis were the motions of the subjects' wrists, elbows, shoulders, hips, knees, and ankles, and the tip of the fin. All points were digitised manually. The high frequency component was extracted using a Butterworth digital low pass filter with 6Hz cutoff frequency. One cycle is defined as the period starting when each body part reached its highest position, and ending when that body part returned to that high position. The coordinates of each body part were calculated by actual length conversion. The time and the coordinates of each body part, we approximated vertical position over time as a sine wave, to more easily calculate the amplitude. This approximation is described here as Formula 1.

\[ z=a_1 \sin (b_1 t+c_1) +d_1 t+e_1 \]  
(Formula 1)

In Formula 1, \( a_1 \) indicates amplitude/2, \( b_1 \) is for frequency, \( c_1 \) is the starting point of the sine wave, \( d_1 \) is the decline of the baseline, and \( e_1 \) indicates the offset of the baseline. The amplitude of each body part is \( 2a_1 \). Kick rate is the average value of \( b_1/2\pi \) for each body part. The horizontal component of hip movement over time was approximated using a linear function, as described in Formula 2 below.
The horizontal velocity \((V_e, \text{m/s})\) was set as \(a_2\). Kick length was calculated by dividing horizontal velocity by kick rate. The data for amplitude of each body part, \(V_e\), kick rate, and kick length were analyzed by Pearson product-moment correlation coefficient. The significance level was set to less than 5%.

**Results**

The correlation coefficients between \(V_e\), kick rate, kick length and amplitude of each body part are indicated in Table 1. No correlation was observed between wrists, elbows, shoulders, hips, and knees, but a significant positive correlation was observed for ankles and fin for male subjects. For female subjects, no correlation was observed between horizontal velocity and the movement of the shoulders and hips, but a negative correlation was found for wrists and elbows. The positive correlation between knees, ankles and fin was not observed. For both males and females, we observed a significant negative correlation between kick rate and all body parts, and a significant positive correlation between kick length and the lower limbs. In males, but not females, we observed a significant positive correlation between kick length and all body parts. For females, no significant correlation was found between kick length and wrists and elbows, but a significant positive correlation was observed between kick length and shoulders, hips, knees, ankles and fin.

**Table 1**

<table>
<thead>
<tr>
<th>Boys</th>
<th>Ve (m/s)</th>
<th>Wrist</th>
<th>Elbow</th>
<th>Shoulder</th>
<th>Hip</th>
<th>Knee</th>
<th>Ankle</th>
<th>Fin</th>
</tr>
</thead>
<tbody>
<tr>
<td>KR (Hz)</td>
<td>-.551 **</td>
<td>-.660 **</td>
<td>-.552 **</td>
<td>-.505 **</td>
<td>-.572 **</td>
<td>-.311 **</td>
<td>-.367 **</td>
<td></td>
</tr>
<tr>
<td>KL (m/kick)</td>
<td>.448 **</td>
<td>.607 **</td>
<td>.687 **</td>
<td>.760 **</td>
<td>.767 **</td>
<td>.888 **</td>
<td>.862 **</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Girls</th>
<th>Ve (m/s)</th>
<th>Wrist</th>
<th>Elbow</th>
<th>Shoulder</th>
<th>Hip</th>
<th>Knee</th>
<th>Ankle</th>
<th>Fin</th>
</tr>
</thead>
<tbody>
<tr>
<td>KR (Hz)</td>
<td>-.570 **</td>
<td>-.660 **</td>
<td>-.554 **</td>
<td>-.565 **</td>
<td>-.551 **</td>
<td>-.242 *</td>
<td>-.270 *</td>
<td></td>
</tr>
<tr>
<td>KL (m/kick)</td>
<td>.063 n.s.</td>
<td>.186 n.s.</td>
<td>.624 **</td>
<td>.772 **</td>
<td>.779 **</td>
<td>.803 **</td>
<td>.856 **</td>
<td></td>
</tr>
</tbody>
</table>

*p<.05, **p<.01

Ve: Horizontal Velocity (m/s), kick rate: Kicking Rate (Hz), kick length: Kicking Length (m/kick). The distance moved forward by one kicking

**Discussion**

With regard to the relationship between horizontal velocity and the amplitude of each body part, no correlation between horizontal velocity and wrists and knees was observed for male subjects, and no correlation between horizontal velocity and shoulders and hip was found for female subjects. To improve the swimming speed of inexperienced monofin swimmers, it is expected that teachers would prioritise training for the body parts associated with speed. Moreover, gender differences were observed for some body parts associated with horizontal velocity. In their functional model of monofin swimming technique, Rejman & Ochmann (2007) indicated, 'Our results pointed out the need to intensify the angular velocity of thigh extension and dorsal flexion of the feet, to strengthen velocity of attack of the tail and to accelerate the attack of the distal part of the fin.' It can be seen that the lower limbs’ muscle power is required to increase swimming speed. Furthermore, Tachi (2003) measured isometric knee joint extension torque and leg extension power, and observed that these values were lower in females in comparison to males. The females who participated in our study are likely to lack the muscular development required for improvement of swimming speed. With regard to the difference in competition level, Geladas et al. (2005) suggested that beginners with little training show greater amplitude for the upper limbs, and a smaller amplitude for the lower limbs, compared to advanced swimmers with more training. The results of this study show a
connection between amplitude of the lower limbs and swimming speed, consistent with the previous study, for both males and females. Regarding the amplitude of the upper limbs, a negative correlation was found between horizontal velocity and amplitude of wrists and elbows for females. No such correlation was found for males, so this finding is not consistent with the previous study. This point can be considered a characteristic of inexperienced male monofin swimmers. Differences in finswimming ability due to competition levels were observed in our female subjects, but may not be observed for males. In conclusion, gender differences were observed in the relationships between horizontal velocity and the amplitude of each body part, but these differences may be affected by differing competition levels.

Nicolas et al. (2007) discussed the possibility of a ‘trade-off’ existing between kick rate and amplitude. If the amplitude of each part of the body is different, kick length and kick rate can be expected to differ as well. The results of this study indicate a negative correlation between the amplitude of each body part and kick rate for inexperienced monofin swimmers, and confirm the existence of the ‘trade-off’. Even when increasing the amplitude to improve swimming speed, a decrease in kick rate is likely, but this is unlikely to improve swimming speed. As a result, in order to improve swimming speed for inexperienced monofin swimmers, it is necessary to perform drills to increase the amplitude of the lower limbs and speed training to improve the maximum kick rate.

On the other hand, there is no report about the relation between kick length and amplitude of each body part. Oshita (2008) compared finalists and non-finalists of the World Championships 50-meter surface race, and found a difference in kick length, but no difference in kick rate. Amplitude was not discussed. Two-dimensional DLT capture with a video camera is mainly used for calculating amplitude, (Nicolas & Bideau 2009). The disadvantage of this method is that it cannot be conducted in actual finswimming competitions, so it requires much time and effort to set up a test site. In contrast, kick length can be calculated by dividing horizontal velocity by kick rate. Horizontal velocity can be calculated by dividing the distance by time, and kick rate can be calculated by dividing the number of kicks by the swimmer’s time. Thus, if the number of kicks can be measured, it is possible to calculate simplified velocity, kick rate and kick length. If the relationship between kick length and amplitude can be understood, it will be possible to estimate the amplitude of the lower limbs from kick length. The results of this study showed a significant positive correlation between kick length and the amplitude of the lower limbs for both males and females. This shows that it is possible to estimate the amplitude if kick length can be calculated. In the future, if the amplitude of the lower limbs can be estimated from kick length, (which is relatively easily calculated,) amplitude can be more easily used as an indicator for training.

Conclusions
The purpose of this study is to verify the relationship between the amplitude of body parts and swimming speed, kick rate and kick length in apnea finswimming by high-school swimmers without monofin swimming experience. Our results allow us to clarify the following three points. 1) Since no correlation was observed between the swimming speed and the amplitude of wrists and knees for males, and the amplitude of shoulders and hips for females, we can conclude that some body parts have no relation to swimming speed. 2) A negative correlation was observed between amplitude and kick rate, which verified the existence of a trade-off between amplitude and kick rate for inexperienced monofin swimmers. 3) A significant positive correlation was observed between kick length and the amplitude of the lower limbs, which indicates that it is possible to estimate the amplitude from kick length.

Acknowledgment
We received instructions and cooperation from many high school swimming club coaches and the many swimming club members who assisted in this study. We would like to take this opportunity to express sincere appreciation to all of you.
Introduction

In competitive swimming, the start has been strongly linked to overall performance (Cossor & Mason 2001). The swimming start can contribute between 0.8-26.1% of total race time depending on the distance (Lyttle & Benjanuvatra 2005), with the percentage contribution increasing as the distance of the race becomes shorter (Hay 1986). The swimming start phase of a race is defined as the time from the starting signal to when the centre of the swimmer’s head reaches 15 m (Cossor & Mason 2001). The start as a whole is typically broken into three sub-phases: the on-block, flight and underwater phases. The percentage time contribution of each sub-phase is approximately 11%, 5% and 84% respectively (Slawson, Conway, Cosser, Chakravorti & West 2013). The on-block phase is described as the time from the starting signal to when the swimmer leaves the block while the flight phase is the time from when the swimmer leaves the block to when the swimmer enters the water. The last and longest phase of the start is the underwater phase and is the time from when the swimmer enters the water to when the swimmer resurfaces to begin free swimming. The free-swimming time is defined as the time following the underwater phase from breakout to 15 m.
Following the Beijing Olympics in 2008 a new starting block was introduced to international competition. The Omega OSB11 starting block has an adjustable kick plate, footrest or back plate fixed at 30° which can be moved to five different locations (35 mm intervals) along the length of the starting platform which is also angled at 10° to the horizontal. As a result of the introduction of these blocks a different starting technique called the ‘kick-start’ has been developed and utilised by most elite swimmers during competition. Multiple research studies have found that swimmers can gain an added advantage using this new technique (Honda, Sinclair, Mason & Pease 2010; Takeda, Takagi & Tsubakimoto 2013). This is mainly due to an increase in horizontal velocity with the added contribution of the increased force that is able to be produced by the rear leg (Honda et al. 2010).

There have been many previous start studies that have compared different start techniques (Blanksby, Nicholson & Elliott 2002), or evaluated different elements of the start such as foot placement (Takeda et al. 2013), entry angle (Groves & Roberts 1972) and starting position (Honda, Sinclair, Mason & Pease 2012). Although these studies have used elite/sub-elite subjects the groups they used were mixed and comparisons between genders were not made. Cossor and Mason (2001) did separate their analysis into male and female groups, however they did not make comparisons between gender. Furthermore, Seifert et al. (2010), Vantorre et al. (2010), Breed et al. (2000), Kirner et al. (1989) examined start performance based only on low-to moderate numbers of single gender subjects. There is obvious strength, performance and technical differences present for males compared to female swimmers so combining genders in the same analysis may not be appropriate, as differences might exist in how velocity is developed.

The same observations can be made when comparing start performances for difference strokes. There are even fewer studies that have combined different strokes in their study design. Only two known studies have compared the differences between freestyle and butterfly starts. Strojnik et al. (1998) found small differences in the flight phase of the start, while Whitten (1997) found that butterfly swimmers travelled deeper during the underwater phase. However, these studies compared the differences between strokes using a grab start technique. Given that the grab start has been superseded by the kick-start, the findings from these studies may not be relevant to techniques currently used in competition.

This study is the first to compare start performances and specific start parameters between male and female using elite swimmers and the new kick-start technique. The aims of this study were to characterise the swim start of elite swimmers using the new Omega OSB11 starting block and to make comparisons between gender and different strokes based on overall start performance.

**Methods**

Retrospective data was utilised in this study to determine the characteristics of the technique elite swimmers adopt during the kick-start using the Omega OSB11 starting block. Ethical approval was obtained from the Ethics Committee of The Australian Institute of Sport. The trials were selected from a database of start performances collected by the Australian Institute of Sport—Aquatic Testing, Training and Research Unit (AIS ATTRU). These trials were then filtered to include trials from able-bodied participants wearing textile training swim wear (eliminating any trials where swimmers wore the now illegal swimsuits) who had made at least one senior Australian national swimming team (Olympics and World Championships) and specialised in either freestyle or butterfly. Once the data was filtered there were a total of 52 trials (29 male, 23 female, aged 22 ± 0.5 y) included in the study (52 swimmers, 1 trial per swimmer). Of these trials 39 swimmers were Olympians (30 Olympic Medallists) and 14 World Championship representatives (11 World Championship Medallists). Of these, 39 were freestyle swimmers and 13 were butterfly swimmers. The Wetplate Analysis System and Swimtrak Timing System were used to collect all data in this study (Mason, Mackintosh & Pease 2012).

Descriptive statistics were calculated for each parameter on a group basis then data were split into above—water parameters (parameters that occurred before the swimmer entered the water) and
underwater parameters (the remaining parameters that occurred after the swimmer entered the water). The Kolmogorov–Smirnov test confirmed all parameters were normally distributed (p > 0.05). Independent t-tests were then used to make comparisons between gender and the strokes using the smaller parameter groupings. Differences in performance were also made using independent t-tests between gender and the different strokes. Effect sizes were then calculated using Cohen’s (d) to determine if the differences between each group were substantive (Cohen 1988). The scale used to determine the size of the effect was 0.2, 0.5, 0.8; small, medium large respectively. All statistics were computed using SPSS software (version 19.0, SPSS, Chicago, IL).

Results

The mean percentage contribution for each phase of the start was calculated. 11% (0.74 s) spent in the on-block phase, 5% (0.30 s) in the flight phase, 56% (3.69 s) in the underwater phase and 28% (1.81 s) free swimming. The mean percent contributions of each start phase were also calculated for each gender; males spent 12% (0.72 s) in the on-block phase, 5% (0.29 s) in the flight phase, 61% (3.72 s) in the underwater phase and 23% (1.39 s) free swimming. For females, 11% (0.77 s) was spent in the on-block phase, 4.1% (0.29 s) in the flight phase, 51.9% (3.67 s) in the underwater phase and 33.1% (2.34 s) free swimming.

A comparison between male and female showed there was a significant difference between overall performance time to 15 m with males 0.95 s faster than females (p < 0.001, Large) (p-value, effect size). This was due to males producing significantly larger take-off horizontal velocity (0.52 m.s\(^{-1}\), p < 0.001, Large), peak horizontal force (0.22 N, p < 0.001, Large) and were also able to produce faster underwater velocities for all segments (Table 1) than females. Males also travelled significantly deeper (0.20 m, p < 0.001, Large). For the underwater parameters there were significant differences in all average velocities and split times, horizontal distance of max depth of head (0.08 m, p = 0.08, Large), underwater velocity (0.27 m.s\(^{-1}\), p < 0.001, Large) and breakout distance (1.33 m, p = 0.02, Small) (Table 2).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Male</th>
<th>Female</th>
<th>Difference in Mean</th>
<th>P Value</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Time (s)</td>
<td>0.72 ± 0.04</td>
<td>0.77 ± 0.05</td>
<td>0.05</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Take-off Horizontal Velocity (m.s(^{-1}))</td>
<td>4.85 ± 0.17</td>
<td>4.33 ± 0.19</td>
<td>0.52</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Take-off Vertical Velocity (m.s(^{-1}))</td>
<td>-1.19 ± 0.46</td>
<td>-1.32 ± 0.36</td>
<td>0.13</td>
<td>0.25</td>
<td>Small</td>
</tr>
<tr>
<td>Time in the air (s)</td>
<td>0.30 ± 0.05</td>
<td>0.29 ± 0.04</td>
<td>0.01</td>
<td>0.35</td>
<td>Small</td>
</tr>
<tr>
<td>Average Acceleration (m.s(^{-1}))</td>
<td>6.76 ± 0.49</td>
<td>5.63 ± 0.47</td>
<td>1.13</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>CoG Angle of Entry (degrees)</td>
<td>45.57 ± 1.56</td>
<td>48.81 ± 1.58</td>
<td>3.24</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Dive Angle (degrees)</td>
<td>-13.71 ± 5.01</td>
<td>-16.93 ± 4.23</td>
<td>3.22</td>
<td>0.02*</td>
<td>Medium</td>
</tr>
<tr>
<td>Entry Distance (m)</td>
<td>2.93 ± 0.16</td>
<td>2.67 ± 0.15</td>
<td>0.26</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Entry Hole Diameter (m)</td>
<td>0.60 ± 0.15</td>
<td>0.72 ± 0.17</td>
<td>0.12</td>
<td>0.01*</td>
<td>Large</td>
</tr>
<tr>
<td>Entry Velocity (m.s(^{-1}))</td>
<td>6.94 ± 0.11</td>
<td>6.59 ± 0.14</td>
<td>0.35</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Head Entry Time (s)</td>
<td>1.01 ± 0.05</td>
<td>1.06 ± 0.05</td>
<td>0.05</td>
<td>0.01*</td>
<td>Large</td>
</tr>
<tr>
<td>Peak Footplate Force (N)</td>
<td>1.70 ± 0.26</td>
<td>1.36 ± 0.18</td>
<td>0.34</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Peak Grab Force (N)</td>
<td>0.96 ± 0.20</td>
<td>0.77 ± 0.20</td>
<td>0.19</td>
<td>0.00*</td>
<td>Large</td>
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<tr>
<td>Peak Horizontal Force (N)</td>
<td>1.33 ± 0.15</td>
<td>1.11 ± 0.15</td>
<td>0.22</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Peak Vertical Force (N)</td>
<td>1.36 ± 0.21</td>
<td>1.21 ± 0.14</td>
<td>0.15</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Peak Power per Kilogram (w/kg)</td>
<td>62.56 ± 8.47</td>
<td>48.65 ± 6.68</td>
<td>13.91</td>
<td>0.00*</td>
<td>Large</td>
</tr>
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*Significant for p < 0.05
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<tr>
<th>Parameter</th>
<th>Male</th>
<th>Female</th>
<th>Difference in Mean</th>
<th>P Value</th>
<th>Effect Size</th>
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<tbody>
<tr>
<td>Time of Full Submersion (s)</td>
<td>1.34 ± 0.05</td>
<td>1.35 ± 0.06</td>
<td>0.01</td>
<td>0.29</td>
<td>Small</td>
</tr>
<tr>
<td>Time After Entry of First Kick (s)</td>
<td>0.42 ± 0.21</td>
<td>0.46 ± 0.24</td>
<td>0.04</td>
<td>0.61</td>
<td>Small</td>
</tr>
<tr>
<td>Time of First Kick (s)</td>
<td>2.01 ± 0.21</td>
<td>2.08 ± 0.28</td>
<td>0.07</td>
<td>0.36</td>
<td>Small</td>
</tr>
<tr>
<td>Horizontal Distance of Max depth (m)</td>
<td>6.29 ± 0.65</td>
<td>5.78 ± 1.22</td>
<td>0.51</td>
<td>0.08</td>
<td>Large</td>
</tr>
<tr>
<td>Max Depth of Head (m)</td>
<td>-1.05 ± 0.20</td>
<td>-0.85 ± 0.21</td>
<td>0.20</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Time at Max Depth (s)</td>
<td>1.88 ± 0.25</td>
<td>2.01 ± 0.55</td>
<td>0.13</td>
<td>0.29</td>
<td>Small</td>
</tr>
<tr>
<td>Time Underwater in Accent (s)</td>
<td>2.85 ± 0.70</td>
<td>2.72 ± 0.77</td>
<td>0.13</td>
<td>0.54</td>
<td>Small</td>
</tr>
<tr>
<td>Time Underwater in Decent (s)</td>
<td>0.86 ± 0.24</td>
<td>0.95 ± 0.55</td>
<td>0.09</td>
<td>0.45</td>
<td>Small</td>
</tr>
<tr>
<td>Total Time Underwater (s)</td>
<td>3.71 ± 0.86</td>
<td>3.68 ± 1.11</td>
<td>0.03</td>
<td>0.91</td>
<td>Small</td>
</tr>
<tr>
<td>Underwater Velocity (m.s(^{-1}))</td>
<td>2.50 ± 0.17</td>
<td>2.23 ± 0.13</td>
<td>0.27</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Breakout Distance (m)</td>
<td>12.10 ± 1.70</td>
<td>10.77 ± 2.06</td>
<td>1.33</td>
<td>0.02*</td>
<td>Small</td>
</tr>
<tr>
<td>Time of Surfacing(s)</td>
<td>4.73 ± 0.87</td>
<td>4.73 ± 1.10</td>
<td>-</td>
<td>0.98</td>
<td>Medium</td>
</tr>
<tr>
<td>Time to 5 m (s)</td>
<td>1.47 ± 0.05</td>
<td>1.67 ± 0.08</td>
<td>0.20</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Time to 7.5 m (s)</td>
<td>2.39 ± 0.08</td>
<td>2.82 ± 0.15</td>
<td>0.43</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Time to 10 m (s)</td>
<td>3.59 ± 0.10</td>
<td>4.22 ± 0.19</td>
<td>0.63</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Time to 15 m (s)</td>
<td>6.12 ± 0.16</td>
<td>7.07 ± 0.28</td>
<td>0.95</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Avg. Velocity 0-5 m (m.s(^{-1}))</td>
<td>3.40 ± 0.12</td>
<td>3.01 ± 0.15</td>
<td>0.39</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Avg. Velocity 5-7.5 m (m.s(^{-1}))</td>
<td>2.74 ± 0.15</td>
<td>2.17 ± 0.18</td>
<td>0.57</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Avg. Velocity 7.5-10 m (m.s(^{-1}))</td>
<td>2.08 ± 0.10</td>
<td>1.79 ± 0.07</td>
<td>0.29</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Avg. Velocity 10-15 m (m.s(^{-1}))</td>
<td>1.98 ± 0.08</td>
<td>1.76 ± 0.10</td>
<td>0.22</td>
<td>0.00*</td>
<td>Large</td>
</tr>
</tbody>
</table>

*Significant for \(p < 0.05\)

When differences between freestyle and butterfly were examined, there were no significant differences between any of the above-water parameters. For the underwater parameters there were nine significant differences (Table 3). The butterfly swimmers had a significantly deeper max depth (0.21 m, \(p = 0.01\), Large) that was further away from the start blocks (0.82 m, \(p < 0.01\), Large), spent more time underwater (1.10 s, \(p < 0.00\), Large), had a higher underwater velocity (0.12 m.s\(^{-1}\), \(p = 0.02\), Medium) and a longer breakout distance (2.24 s, \(p < 0.00\), Large) than the freestyle swimmers. The medium effect sizes found for take-off vertical velocity, time in the air, dive angle and entry hole diameter further suggest that even though there was no statistical significance there were some differences which may account for the difference in underwater parameters between strokes.
Table 3  
Underwater parameter comparison between freestyle and butterfly

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Freestyle</th>
<th>Butterfly</th>
<th>Difference in Mean</th>
<th>P value</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of Full Submersion (s)</td>
<td>1.34 ± 0.05</td>
<td>1.35 ± 0.06</td>
<td>0.01</td>
<td>0.79</td>
<td>Small</td>
</tr>
<tr>
<td>Time After Entry of First Kick (s)</td>
<td>0.43 ± 0.23</td>
<td>0.46 ± 0.21</td>
<td>0.03</td>
<td>0.70</td>
<td>Small</td>
</tr>
<tr>
<td>Time of First Kick (s)</td>
<td>2.04 ± 0.26</td>
<td>2.06 ± 0.17</td>
<td>0.02</td>
<td>0.81</td>
<td>Small</td>
</tr>
<tr>
<td>Horizontal Distance of Max depth (m)</td>
<td>5.86 ± 0.95</td>
<td>6.68 ± 0.77</td>
<td>0.82</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Max Depth of Head (m)</td>
<td>-0.91 ± 0.21</td>
<td>-1.12 ± 0.22</td>
<td>0.21</td>
<td>0.01*</td>
<td>Large</td>
</tr>
<tr>
<td>Time at Max Depth (s)</td>
<td>1.87 ± 0.39</td>
<td>2.16 ± 0.40</td>
<td>0.29</td>
<td>0.04*</td>
<td>Large</td>
</tr>
<tr>
<td>Time Underwater in Accent (s)</td>
<td>2.59 ± 0.67</td>
<td>3.40 ± 0.53</td>
<td>0.81</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Time Underwater in Decent (s)</td>
<td>0.83 ± 0.39</td>
<td>1.12 ± 0.39</td>
<td>0.29</td>
<td>0.03*</td>
<td>Medium</td>
</tr>
<tr>
<td>Total Time Underwater (s)</td>
<td>3.42 ± 0.92</td>
<td>4.52 ± 0.58</td>
<td>1.10</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Underwater Velocity (m.s(^{-1}))</td>
<td>2.41 ± 0.22</td>
<td>2.29 ± 0.13</td>
<td>0.12</td>
<td>0.02*</td>
<td>Medium</td>
</tr>
<tr>
<td>Breakout Distance (m)</td>
<td>10.95 ± 1.84</td>
<td>13.19 ± 1.31</td>
<td>2.24</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Time of Surfacing (s)</td>
<td>4.46 ± 0.92</td>
<td>5.56 ± 0.61</td>
<td>1.10</td>
<td>0.00*</td>
<td>Large</td>
</tr>
<tr>
<td>Time to 5 m (s)</td>
<td>1.56 ± 0.12</td>
<td>1.56 ± 0.11</td>
<td>-</td>
<td>0.98</td>
<td>Small</td>
</tr>
<tr>
<td>Time to 7.5 m (s)</td>
<td>2.60 ± 0.26</td>
<td>2.53 ± 0.22</td>
<td>0.07</td>
<td>0.41</td>
<td>Small</td>
</tr>
<tr>
<td>Time to 10 m (s)</td>
<td>3.90 ± 0.36</td>
<td>3.79 ± 0.31</td>
<td>0.11</td>
<td>0.29</td>
<td>Small</td>
</tr>
<tr>
<td>Time to 15 m (s)</td>
<td>6.55 ± 0.54</td>
<td>6.50 ± 0.51</td>
<td>0.05</td>
<td>0.74</td>
<td>Small</td>
</tr>
<tr>
<td>Avg. Velocity 0-5 m (m.s(^{-1}))</td>
<td>3.23 ± 0.25</td>
<td>3.23 ± 0.23</td>
<td>-</td>
<td>0.99</td>
<td>Small</td>
</tr>
<tr>
<td>Avg. Velocity 5-7.5 m (m.s(^{-1}))</td>
<td>2.45 ± 0.33</td>
<td>2.59 ± 0.31</td>
<td>0.14</td>
<td>0.17</td>
<td>Medium</td>
</tr>
<tr>
<td>Avg. Velocity 7.5-10 m (m.s(^{-1}))</td>
<td>1.94 ± 0.18</td>
<td>2.01 ± 0.15</td>
<td>0.07</td>
<td>0.16</td>
<td>Medium</td>
</tr>
<tr>
<td>Avg. Velocity 10-15 m (m.s(^{-1}))</td>
<td>1.89 ± 0.14</td>
<td>1.85 ± 0.14</td>
<td>0.04</td>
<td>0.40</td>
<td>Small</td>
</tr>
</tbody>
</table>

*Significant for p < 0.05

Discussion

The data in this study supersedes previous studies of start techniques that are no longer used nor relevant to current competition techniques. In fact, swimmers can now gain an added advantage from using the additional kick plate on the new Omega OSB11 blocks. Honda et al. (2010) found that swimmers were able to produce more horizontal velocity off the blocks using the kick-start technique, which resulted in faster split times to 7.5 m.

The mean percentage time and absolute time contributions for each sub-phase of the swimming start in this study were in line with several previous swimming start studies using a variety of older start techniques. The on-block and flight phase contributions were the same as Blanksby et al. (2002) and Mason et al. (1997). Previous studies have not determined the exact time contribution of the underwater phase to overall start performance. Hence, in this study the time from head entry to 15 m was divided into two sections; the underwater and free-swimming phases. The swimmers spent the longest time in the underwater phase compared to the other sections of the start, which highlights its importance to overall start performance. Similar conclusions can be drawn when comparing the percentage contributions of each phase between genders. There were little differences between the on-block and flight phases. The main variances between male and female occurs during the underwater and free-swimming phases. Females had slower overall start performances, spent slightly less time underwater and more time free-swimming. From the results in this study there is evidence that the percentage time contributions are the same regardless of start technique and similar for gender. Therefore, the improvements in performance that come from the kick-start technique are due to the increase in magnitude of contribution of each sub-phase to overall start performance.

There were multiple differences between male and females which resulted in differences in performance. Male swimmers were faster, produced larger velocities and forces when compared to females. This is the same as an earlier study on elite swimmers by Miller et al. (1984). Furthermore, there were significant differences and large effects in take-off horizontal velocity (0.52 m.s\(^{-1}\), p <
0.001, Large), average acceleration \((1.13 \text{ m.s}^{-1}, p < 0.001, \text{Large})\) and entry velocity \((0.35 \text{ m.s}^{-1}, p < 0.001, \text{Large})\), which is the result of males being able to generate larger amounts of force. Therefore, the higher take-off horizontal velocity displayed by the males was a result of the significant differences in peak horizontal force \((0.22 \text{ N}, p < 0.001, \text{Large})\).

For the underwater parameters there were also significant differences between genders. The differences occurred for max depth of head \((0.20 \text{ m}, p > 0.001, \text{large})\) and breakout distance \((1.33 \text{ m}, p = 0.02, \text{small})\). Males also had significantly higher underwater velocity split times and average velocity for all distance intervals. This was most likely due to the higher velocity the males are able to generate during the previous two phases of the start. Lyttle and Benjanuvatra (2005) stated that the phases preceding the swimmer’s entry into the water (on block phase and flight phase) will directly affect the velocity the swimmer is able to achieve during the underwater phase of the start which is similar to the findings of this study. As both genders stayed underwater for approximately the same time the males were able to travel further due to higher underwater velocity than the females which resulted in better overall start performances. This finding supported those of Miller et al. (1984) who attributed the longer breakout distances in males to their greater height. However, height was not measured in this study so this point cannot be validated using the data from the present study.

Differences also existed between strokes for the underwater phase of the start but not for above-water parameters. This was different to the findings of Strojnik et al. (1998) who reported only small non-significant differences between each stroke during the swimming start. When compared to previous research, the results from this study displayed some significantly different values, particularly with the underwater parameters. Whitten (1997), from the analysis of grab starts also found that butterfly swimmers dive deeper that freestyle swimmers. A possible explanation for this may be that butterfly swimmers have a greater proficiency for the kick used in the underwater phase of the start, as its mechanics are similar to the kick used in the free swimming butterfly stroke. This would result in butterfly swimmers being able to achieve higher underwater velocities. However, even though butterfly swimmers spent longer and travelled faster underwater there were no significant differences in overall start performances or split times. This would suggest that freestyle swimmers commence free swimming earlier and are able to compensate for a slower underwater velocity with higher free-swimming velocity.

**Conclusion**

This study was the first to use an instrumented start block and elite swimmers to characterise the main differences between male and female swimmers as well as examining differences between freestyle and butterfly starting technique. The importance of the underwater phase was clearly highlighted as swimmers spent the longest time in this phase and had the largest contribution to start performance. Practically, coaches and swimmers should therefore place emphasis on improving the underwater phase. The results also show that there are clear variances in start performance between male and female athletes due to males being able to generate greater force and velocity in the early phases of the start which translate into faster overall start performances. There are also differences present for underwater parameters when comparing butterfly and freestyle, however these differences do not result in differences in time to 15 m.

**References**


A new method to evaluate breaststroke kicking technique using a pressure distribution analysis

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Keywords: swimming, fluid forces, propulsion, direct measurement

Introduction

The propulsive force produced by limbs is a key contributor to the velocity attained during human swimming. However, the swimming motion in the aquatic environment is very complex, being difficult to evaluate the propulsive forces. Although many researchers have developed direct method to measure active drag during human swimming (Hollander et al. 1986; Formosa, Mason & Burkett 2011), the situation differs from that in free swimming.

To circumvent these difficulties, a new method has been developed in which fluid forces are estimated from analysis of pressure distributions (Takagi & Wilson 1999; Kudo et al. 2008). This method has been used to successfully measure the force acting on a hand over time. As swimmers...
move their hand through the water, the pressure fluid drag forces act perpendicularly to the hand surface. Swimmers are propelled by the reaction force that matches the sum of these fluid forces. Estimating fluid forces by analyzing pressure distributions confers a distinct advantage over conventional measures: swimming technique is undisturbed and, provided that the pressure drag is measured directly, errors in the estimated fluid forces appear to be reduced.

However, no methodology has been proposed for predicting the fluid forces acting on other parts of a swimmer’s body. Especially in the breaststroke, the propulsive forces produced by lower limb motions are more important than those produced by upper limb motions. Therefore, while an improved kicking technique would seem to be essential to performance of the breaststroke. If the fluid forces produced by breaststroke kicking could be measured precisely, coaches and swimmers would be better equipped to evaluate their technical training. In addition, if the reliability of a methodology for estimating the fluid forces acting on a foot during breaststroke kicking could verified, then coaches and swimmers could apply this information.

The purpose of this study was to develop a new method for evaluation of breaststroke kicking motion using a pressure distribution analysis around a foot.

**Method**

**Experimental design**

To achieve the purpose, two experiments were carried out. In the first experiment, we investigated the reliability of estimated fluid forces by using a robotic leg to which a model foot was affixed. The robotic leg could reproduce breaststroke kicking motions. As a breaststroke kicking motion was generated, the pressure distribution around the model foot was measured. In the second experiment, to test the possibility of using this method to evaluate the kicking techniques of actual swimmers, eleven national-level male swimmers participated in this experiment. Swimmers performed the breaststroke kicking motion at maximal effort without upper limb motions. During the trial, kicking techniques of actual swimmers were analyzed using the methodology tested in the first experiment.

**First experiment**

Experiments were conducted in a circulating water channel. The robotic leg comprised the trunk, hip, thigh, and shank of a human left leg (Figure 1). The robotic leg was designed by Nakashima and Takahashi and constructed at the Akishima Laboratory, Mitsui Zosen Inc., Japan. The hip joint has three degrees-of-freedom (DOF), and knee joint has a DOF. Breaststroke-kicking motions were reproduced by combinations of these four motions.

The robotic leg performed two types of breaststroke-kicking motions (standard and large) at two speeds of the joint angles (6.4 s/cycle and 8.0 s/cycle). The joint angles of the standard trial were based on kinematic swimming data from an international-level female swimmer. The ranges of joint angles in the large trial were adjusted to be larger than those in the standard trial. Additionally, to clarify the influence of fluid forces on the foot model alone, trials were conducted on the robotic leg that was not mounted to the model foot.

The robotic leg was fixed from above the water channel with a three-dimensional load cell (LSM-E Kyowa Electronic Instruments Co. Ltd., Japan). The forces measured by the load cell were processed using a sensor interface (PCD3308-F Kyowa Electronic Instruments Co. Ltd., Japan), sampled at 200 Hz and input to a personal computer.

The foot model (Figure 1) was 0.217 m long, 0.086 m wide, 0.080 m high, and weighed 0.804 kg. The projected areas on the horizontal and sagittal planes were 133.20 cm² and 122.75 cm², respectively. The foot model was constructed from silicone and was molded from the left foot of a female swimmer. Eight pressure sensors (PS05-KC Kyowa Electronic Instruments Co. Ltd., Japan) were embedded in a grooved chassis that conformed to the foot surface.
Fluid forces were estimated from pressure distributions and areas of the foot model using a modification of the methodology reported by Takagi and Wilson (1999). The sensors measured flow-induced hydrodynamic pressures, as well as hydrostatic pressures due to the depth of the sensors. Hydrostatic pressures were eliminated by subtracting dorsal pressures from those at the plantar sides, enabling values for effective hydrodynamic pressures to be obtained. In the present study, the toe end of the foot was divided into three segments, while the heel end was defined as a single segment (Figure 2). These four segments were divided according to six anatomical landmarks, and four pairs of pressure sensors were embedded into the dorsal and plantar sides of each segment. Hydrodynamic pressures were calculated as pressure differences between dorsal and plantar sides. These calculated pressure differences were assumed to represent the pressure differences at the segment. Multiplying those pressure differences by the area of each segment yields the fluid forces acting on each segment. The fluid forces acting across the entire foot model were obtained by summing the forces calculated at each segment. When calculating pressure differences, angles between pairs of pressure sensors were taken into account by measuring the angles at the sagittal plane between the dorsal and plantar sides of the foot model in the standing position. The pressure data collected from the pressure sensors were processed via a sensor interface linked to the loadcell, sampled at 200 Hz and fed into a personal computer together with force data and joint angles.

![Robotic leg and foot model](image)

(a) Robotic leg

(b) Foot model

**Figure 1** Robotic leg and foot model used in the first experiment

![Foot model construction](image)

**Figure 2** Construction of the foot model, showing the four segments, and the points where pressure sensors were attached

The breaststroke-kicking motion involves non-propulsive glide and recovery motions as well as propulsive motion. Here we focused, not only on the cycle of kicking motion, but also on the propulsive phase of fluid forces. The relationship between estimated fluid forces from pressure
distribution analysis and the fluid forces measured by the load cell was quantified by Pearson’s correlation coefficient ($r$).

**Second experiment**

To test the possibility of using this method to evaluate the kicking techniques of actual swimmers, seven male swimmers (age: 21.3 ± 2.2 year, height: 1.79 ± 0.06 m, mass: 71.9 ± 7.1 kg, 100 m breaststroke best record: 62.27 ± 0.86 s) participated in this study. The protocol was fully explained to the participants before they provided written consent to participate in the study, which was approved by the university ethics committee. Each swimmer performed the breaststroke kicking motion for ten seconds again without upper limb motions but using kickboard at maximal effort.

During the trial, swimmers were connected to a load cell via a polyethylene rope and a belt for measurement of tethered force at 200 Hz. Eight pressure sensors were attached to the right foot to measure the pressure distribution around the foot in the same manner as was used on the foot model attached to the robotic leg. Fluid forces acting on the foot during the trial were estimated using the same procedure described in the method of the first experiment. The trials were recorded by two backward underwater cameras and a lateral camera (frequency: 60 Hz, shutter speed: 1/500 s). Using coordinates of the right foot calculated using the 3D-DLT method, estimated fluid forces were resolved into propulsive force, vertical force, and lateral force. The competitive swimming velocity ($v_{50}$, $v_{100}$ and $v_{200}$) was calculated based on the personal best time over 50m, 100m and 200m breaststroke respectively. Pearson’s correlation coefficient ($r$) was used to investigate the relationship among the estimated fluid forces, mean of tethered forces, and competitive swimming velocity.

**Results**

In the first experiment which used the robotic leg, Pearson’s correlation coefficient ($r$) revealed significant correlations between the estimated fluid forces from pressure distribution analysis and the fluid forces measured by the load cell (Table 1). These correlations can be seen in temporal profiles of the estimated fluid forces from pressure distribution analysis and the fluid forces measured by the load cell over one kicking cycle for each trial (Figure 3).

<table>
<thead>
<tr>
<th></th>
<th>$F_{\text{loadcell}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum (N)</td>
</tr>
<tr>
<td>Maximum $F_{\text{pressure}}$ (N)</td>
<td>0.77**</td>
</tr>
<tr>
<td>Impulse of $F_{\text{pressure}}$ (N·s)</td>
<td>0.79**</td>
</tr>
<tr>
<td>Impulse of $F_{\text{pressure}}$ at propulsive phase (N·s)</td>
<td>0.82**</td>
</tr>
</tbody>
</table>

* : $p < .05$   ** : $p < .01$
Table 2  Competitive swimming velocities, tethered forces, and variables of estimated fluid forces for each swimmer in the second experiment

<table>
<thead>
<tr>
<th></th>
<th>v50 (m/s)</th>
<th>v100 (m/s)</th>
<th>v200 (m/s)</th>
<th>Mean of tethered force (N)</th>
<th>Mean of fluid forces (N)</th>
<th>Mean of propulsive forces (N)</th>
<th>Maximum of fluid forces (N)</th>
<th>Maximum of propulsive forces (N)</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>1.747</td>
<td>1.628</td>
<td>1.515</td>
<td>288.0</td>
<td>85.7</td>
<td>54.2</td>
<td>313.5</td>
<td>261.1</td>
</tr>
<tr>
<td>B</td>
<td>1.789</td>
<td>1.628</td>
<td>1.505</td>
<td>179.3</td>
<td>55.9</td>
<td>34.3</td>
<td>268.4</td>
<td>187.8</td>
</tr>
<tr>
<td>C</td>
<td>1.759</td>
<td>1.620</td>
<td>1.497</td>
<td>319.7</td>
<td>78.4</td>
<td>57.3</td>
<td>315.1</td>
<td>259.0</td>
</tr>
<tr>
<td>D</td>
<td>1.711</td>
<td>1.609</td>
<td>1.488</td>
<td>214.5</td>
<td>59.8</td>
<td>46.6</td>
<td>223.6</td>
<td>206.0</td>
</tr>
<tr>
<td>E</td>
<td>1.746</td>
<td>1.600</td>
<td>1.448</td>
<td>254.4</td>
<td>42.9</td>
<td>26.9</td>
<td>221.1</td>
<td>175.3</td>
</tr>
<tr>
<td>F</td>
<td>1.668</td>
<td>1.591</td>
<td>1.507</td>
<td>179.9</td>
<td>30.0</td>
<td>22.5</td>
<td>141.9</td>
<td>107.7</td>
</tr>
<tr>
<td>G</td>
<td>1.613</td>
<td>1.567</td>
<td>1.425</td>
<td>187.2</td>
<td>33.2</td>
<td>19.5</td>
<td>139.2</td>
<td>100.4</td>
</tr>
<tr>
<td>Mean</td>
<td>1.719</td>
<td>1.606</td>
<td>1.484</td>
<td>231.9</td>
<td>55.1</td>
<td>37.3</td>
<td>231.8</td>
<td>185.3</td>
</tr>
<tr>
<td>SD</td>
<td>0.060</td>
<td>0.022</td>
<td>0.034</td>
<td>56.5</td>
<td>21.4</td>
<td>15.4</td>
<td>72.8</td>
<td>64.5</td>
</tr>
</tbody>
</table>

Table 3  Pearson’s correlation coefficient (r) between swimming performance and estimated fluid forces in the second experiment

<table>
<thead>
<tr>
<th></th>
<th>v50 (m/s)</th>
<th>v100 (m/s)</th>
<th>v200 (m/s)</th>
<th>Mean of tethered forces (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean of fluid forces (N)</td>
<td>.647</td>
<td>.829*</td>
<td>.564</td>
<td>.777*</td>
</tr>
<tr>
<td>Mean of propulsive forces (N)</td>
<td>.592</td>
<td>.777*</td>
<td>.584</td>
<td>.772*</td>
</tr>
<tr>
<td>Maximum of fluid forces (N)</td>
<td>.843*</td>
<td>.911**</td>
<td>.552</td>
<td>.758*</td>
</tr>
<tr>
<td>Maximum of propulsive forces (N)</td>
<td>.756*</td>
<td>.858*</td>
<td>.532</td>
<td>.817*</td>
</tr>
</tbody>
</table>

**: p < .01, *: p < .05

In the second experiment, competitive swimming velocity, mean of tethered forces, and variables of the estimated fluid forces for each swimmer were shown in Table 2. Pearson’s correlation coefficient (r) revealed significant correlations among the estimated fluid forces, the propulsive forces, mean of tethered forces, and competitive swimming velocity (Table 3). During the trial, the propulsive force, the vertical force, and the lateral forces corresponded to the kicking motions (Figure 4). In propulsive force, positive values mean the fluid forces acting backward of a swimmer. In vertical force, positive...
values mean the fluid forces acting upward of a swimmer. In lateral force, positive values mean the fluid forces acting toward left direction of a swimmer. And below graph shows pressure differences measured in each point where pressure sensors were attached.

**Discussion**

The estimated fluid forces acting on the foot model determined from pressure distribution analysis correlated significantly with the fluid forces measured by the load cell. The possibility of using pressure distribution analysis to evaluate the breaststroke technique of swimmers was evaluated in a series of experiments involving actual swimmers. The estimated fluid forces acting on a foot correlated significantly with actual competitive swimming velocities and mean of tethered forces. Characteristics of the kicking technique could be monitored from fluctuations in the propulsive forces, vertical forces, and lateral forces.

The present methodology, which estimated fluid forces during breaststroke kicking by pressure distribution analyses, could be applied to actual swimmers, and we could use those estimates to monitor the kicking techniques. Although the maximum and mean values of tethered forces correlate significantly with competitive swimming velocity, when the cable becomes slack the tethered force goes zero. Thus, tethered swimming can be used to evaluate propulsive force, but it cannot provide intra-cycle fluctuations in forces. In contrast, since pressure distribution analysis can monitor such fluctuations, swimmers and their coaches can identify more detailed and specific technical problems.

In the present method, the hydrostatic pressure was eliminated by attaching pressure sensors in pair, which simplified the determination of estimates for fluid forces. Thus, fluid forces can be estimated more easily and conveniently than the method reported by Kudo et al. (2008). We conclude that the present methodology can be used to evaluate breaststroke-kicking motions qualitatively and quantitatively, thereby assisting swimmers and their coaches in evaluating and improving their training.

![Figure 4](image_url)  
**Figure 4** Estimated fluid forces acting on the each direction (above), and pressure differences measured in each points (below).
**References**


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**Real-time sonification in swimming— from pressure changes of displaced water to sound**

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**Introduction**

The communication about the swimmers’ internal perception of flow and the movement control is hampered because of missing mutual information about effect of interaction of actions of limbs and invisible motion of displaced (clear) water. Interaction as part of the connectivity of a two-bodies energy sphere. According to Schack (2004) the sensory picture of a voluntary action is a template to organise motor commands and guide motor control. It is widely known that elite swimmers have an excellent perception of water motion using somatosensory, proprioceptive or vestibular and visual cues. Swimming as a self-induced activity in aquatic space means displacing water mass at low energy costs while yielding high swimming speeds in reaction and this is what elite swimmers strive to reach using a right feel for water. Takagi & Wilson (1999) emphasised that without pressure no propulsion exists and a pressure differential method is potentially a useful means in stroke analysis of cyclic 3D hand action. Pressure-time recordings are ‘essential complementary information’ (Loetz et al. 1988) helping to detect wrong hand positions when unusual pressure graphs occur (Van Manen et al. 1975). Klauck & Ungerechts (1997) pointed out that the interaction goes with pressure changes and momentum-induced effects of displaced water mass while drag—even if it is repeated often—does not explain the interaction effects sufficiently. Hence, kinematics of limbs’ actions is not necessarily a direct indicator of flow effects. Ungerechts & Klauck (2014) highlighted that interaction is a means to transfer metabolic energy via limb’s action to a unit volume of water which changes the energy-density, known as ‘pressure’ which in liquids or currents differs from the term pressure solid body mechanics (although in both cases the physical unit is [Pa]). Hermann et al. (2012) pointed out the importance of change of pressure, as an ‘intermediate level’ (Fig. 1) in connection with momentum-induced locomotion in aquatic space, a level which lacks attention in most swimming literature.
Presenting pressure changes as graphs lacks interactive aspects. Therefore the idea came up to use interactive sonification as an audible real-time feedback for the swimmer and the coach, simultaneously. Sonification is a means to map any data-flow like static pressure into functional sound emphasising cognitive attentiveness for the essential aspects in noisy surrounding (which is more than just rhythm or change in pitch). Using audible signals as an information carrier like fishes do (profiting from the fact that pressure wave and sound wave are similar) also exists in human swimming. Kliche & Effenberg (1996) presented a breaststroking avatar while the kinematic data of wrists and ankles were made audible using ‘Fairlight Aahs’. Following Effenberg & Mechling (2005) interactive sonification improve motor performance and perception of movements, after the individuals became acquainted to the functional sound and motor auditory systems were co-activated (the relationship of cognitive levels is still a matter of multi-disciplinary research). It can be expected that swimmers, even without detailed introduction into sound perception, will optimise their perception of displaced water and thus increase performance. Moreover sonification may highlight novel aspects concerning local change of pressure and allows for a fruitful communication of aquatic events between different experts. The sonification of the intermediate level demands the selection of tools like pressure probes, pressure sensors, sonification program, loudspeakers and equipment joint in a new setting enabling operation at the deck of a pool. Before this new approach of augmented perception can be used widely e.g. as a support for talks between swimmer and coach or in cognitive studies, the device needs to be tested. It is the purpose of this paper to inform about the new setting how to generate auditory movement information, to give report on the mapping selected and the quality of the real-time feedback issue.

Materials and methods

The particularity of liquid substance demands an appropriate tool to represent the intermediate level effects (Fig 1) namely the changes of static pressure or change of energy-density in a water volume (b2) in flowing water due to non-steady interaction of body and water mass. The focus on changes in static pressure (not the same like the water column induced hydrostatic pressure) for sonification is justified because it represents the origin of the work done on the water (Webber et al. 2001). Historically the omnidirectional static pressure component (b2) in a current is measured by means of a Piezo-probe, which is a tube bluntly ending normal to the surface of an object, always perpendicular to the stream line (Fig. 2):
Piezo-probes are established tools to measure the change of energy-density in a water volume (pz) (e.g. around a hand) due to interaction (Ungerechts 1981). Whether some energy is added to water volume via body motion and accelerates (thrusting) water or the flow per unit volume slows down (braking) can be substantiated by the difference between two probes values (pz). The setting to determine the effect of the hand action on the water mass and the transfer into sound is presented in Fig. 3.

Instrumentation of swimmers
The openings of Piezo-Probes, 2 per hand, were placed parallel to the surface, respectively; the connecting tube fastened to lower, upper arm and between the scapulae ending in the waterproof box with microcontroller and sensors, attached to a fishing rod; the rod was held by an assistant at pool deck who also carried the hawker’s tray with PC and loudspeakers (Fig. 4).
Selection of sound mapping

SuperCollider provides qualified functional sound and the mapping of changing pressure data (pz) can be based on modulation of e.g. pitch, amplitude, loudness, loudspeaker orientation. Because of continuous flow of sound is repeated over a longer period in time (depending of the period to cover a certain distance from 25 m to 400 m) the mapping should be aesthetically accepted by the recipient to fulfill the task of a supplement feedback. Cesarini et al. (2013) investigated a 12 tones scale for usage on a mobile system in rowing sonification. It was noticed that using either approach, discrete or continuous actually enhances different aspects of the original signal. Grond & Hermann (2012) emphasised ‘Parameter mapping sonification (PMSon) involves the association of information with auditory parameters for the purpose of data display’. PMSon provides a way to build a repeatable transformation from the domain of the monitored signal to that of human hearing. Before applying PMSon to data the actual difference of palmar to back pressure value is calculated. Then the left hand difference and the right hand difference pressures (pz) were fed into the particular PMSon, respectively. The selected mapping is a 3-tone scale mapping (stepwise) using the SuperCollider code: (55+leftPressure.linlin(0,5000,0,24)).round(3).midicps) according to the Handbook of Sonification (Hermann et al. 2011). The code represents a linear conversion from pressure values to midi numbers, rounding the result to 3 (obtaining a 3-tone scale), and finally the midi number is converted to the correct frequency value to be played back by the synthesiser. The stepwise mapping is selected to yield some aesthetics emphasising better perception of pronounced changes in the data-flow; in addition sound of left and right hand was presented on left and right loudspeaker, respectively.

Qualification of real-time aspect in terms of latency

The processes of this new setting of tools required some time and the latency of the setting needs to be evaluated. Here latency means the time delay between the voluntary start of out-sweep hand action causing change of (pz) until the sound is emitted via loudspeakers. To check the latency a fully instrumented breaststroke swimmer was videotaped (30 fps) swimming with extremely long gliding phases in a 25 m pool. The time instant when the hands started sweeping outwards was determined from the video and the time instant of emitted sound was determined after the video’s soundtrack was transferred to an Audacity program (Fig. 5).

Figure 5  Density cloud including the total noise of a swimming pool plus the sound from the loudspeakers; a vertical line indicates the start of the sound induced by pressure changes (pz) due to the start of the hand action after gliding

The difference of both time instants represent the latency. There is no proof value existing in the literature but probably this time should be related to the time of cognitive control loops.

Results

First, the pressure data (pz) were checked. It was shown, the pressure data (pz) per crawl stoke cycle perfectly match in magnitude and dynamic behavior to what is found in literature (Toussaint et al. 2002) using different type of pressure sensors.
Next, the latency or the quality of the real-time aspect was checked quantitatively using a test when the swimmer swam breaststroke with a remarkable long glide; per 25 m lane 8 breaststroke cycles were executed.

The time duration between the voluntary start of outsweep hand action and the sound emitting via loudspeakers was in the range between $|100 – 123|$ ms (Fig. 7) while the mean is $123 \pm 27$ ms. A difference of one video frame equals 33 ms. The calculation of latency due to the ‘internal’ time of the ‘electronic’ transit of the setting gives 14,6 ms.

**Discussion**

Different pressure zones on the palm and the back might resemble Bernoulli’s approach used in steady flow to explain circulating flow components; in non-steady flow with drastically changes of acceleration Bernoulli’s approach does not apply (Matsuuchi et al. 2009; Ungerechts & Klauck 2008). Using the presented Piezo-probe based setting for sonification of change of energy density per volume (p2) due to disturbed water mass in aquatic actions can be advised. An identification of the effect of the sound mappings on the swimmers actual motoric activities was not of priority of this first testing. All subjects told a) the tubes did not disturb stroking and b) the real-time quality was perceived as if ‘each action in water gives immediate reaction’. The real-time check yields positive results, because a delay of 123 ms is not far from reaction threshold of sportive actions.

The functional sound designs selected here is not yet fixed. There will be the choice of two functionality opposite schemes which needs to be deeper analyzed and tested: discrete mappings allow having an enhanced perception of changes of signals, representing the change in a complete new tone, whereas continuous mappings allow perceiving changes in the signal immediately in the output sound at expense of level of perception; the latter is especially important considering that the sounds should be listened to while performing movements in water. The selection of the 3-tone scale mapping (sounds more aesthetic than a continuous one) was not accidentally because of experience...
with former mappings of pressure curves (Hermann et al. 2012). One might assume that the relatively small number of trials is a limitation of our study and it is too early to judge which mapping would please the swimmer when using the real-time sonification of displaced water in training situation as well as to report which mapping is functionally the most appropriate for the non-steady flow situation.

**Future perspectives**

This paper concentrates on individual swimmers to increase his/her ability to perceive water motion in combination with self-perception of the body action. The interactive sonification of pressure data might have the potential as augmented feedback to the swimmer directly and as a support to communicate about flow and sensation of flow. Since the link between kinematics of the hand and the resulting body motion is not yet fully understood sonification -probably in conjunction with an effect variable like intracyclic velocity-variation- a better communication between swimmers/experts about flow and the sensation of flow is needed.

**Figure 8**  Schema of a new approach of training communication using a new setting

The real-time sonification of pressure changes due to displaced water mass is expected a major step towards the aims a) to enhance interrelated perceptions of effects of actions via sound (instead of prescribing a movement) and b) to discover unknown relevant patterns of the (non-steady flow) data. Real-time sonification of is undoubtedly a promising tool for training sessions with elite swimmers at least concerning two aspects: one is related to the cognition-levels of the swimmer who can now use another channel together with the existing own neural network concerning the intimate ‘feel for water’-competence and the other aspect is a completely new way of communication between coach and (elite) swimmers about a more effective action of hands (Fig 8). If communication about sensing the flow, a somewhat neglected topic until now, surely will lead to improvements is likely but need to be examined. Compared to ‘informative paddles’ introduced by Chollet et al. (1992) for real-time auditive feedback of manual hydrodynamic pressure to the swimmer the new setting provides some developments. Here the hand needs not to be equipped with paddles, no ‘chosen strength limit’ needs to be overtaken and the conflict of mixing terms like ‘hydrodynamic pressure’, ‘static pressure’ and ‘hydrodynamic forces’ is solved because the new setting is opt to be sensitive to static pressure (which is not possible with the paddles). In summary, swimmers benefit from this interactive bio-feedback as a ‘self-control means’ learning, coaches will be informed more detailed and experts from flow physics could use the original pressure-time-data for analysis of non-steady flow behavior.

**Literature**


The determination of ‘added mass’ of swimmers as a part of studies of non-steady flow patterns

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1Biomechanics, SPOHO Cologne, 2Neucognition-Biomechanics, University Bielefeld, Germany

Keywords: non-steady flow, virtual added mass, semi-tethered, accelerated swimmer, steady drag-factor

Introduction

Swimmers displace mass of water because there cannot be two bodies which share the same space. Due to the cyclic interaction of body and water mass there are flow effects on the body beyond common consideration of thrust and drag known from steady flow mechanics which was developed for ship construction. A ship, with given shape, should not sink and not produce too much drag to keep the energy costs low. Concerning ships the ‘hull’ is separated from the propulsive propellers and flow effects are sufficiently described by using steady flow mechanics. In contrast, biological
organisms produce thrust and resistance simultaneously during cyclic self-produced propulsion of bodies changing their body form. The cyclic actions prevent flow phenomena from being constant and changes of velocity (acceleration) influence the interaction effects profoundly. These time-space effects are better explained using non-steady flow physics which is not a synonym for turbulent flow of any boundary layer due to viscosity (Lighthill 1969). Scarcely any publication on sport swimming or various activities in aquatic space is touching the flow effects of unsteady water mass. Change of motion of water mass cause momentum change which give raise to effects either in or against swimming direction (Matsuuchi et al. 2006); the saying ‘push off from water’ cannot be supported, even not for didactical purpose because ‘giving way’ is elementary for a fluid.

Interest of non-steady flow phenomena can be extended to all activities in aquatic space and is not limited to sport swimming. Also when dealing with health related activities it is necessary to understand which momentum changes are involved when e.g. swinging the leg to and fro below waterline which is also accompanied by change of motion of water mass. In this text the aspects of non-steady flow physics will exemplified by a general situation of locomotion in water: the gliding after start and push off from a wall. It seems as if everything is clear what happens: the speed of a swimmer will slow down according to the effect of drag. However, studies reveal that the data of gliding distance based on calculation using steady flow mechanics laws do not match with the data gained experimentally; swimmers glide further than calculated (Klauck 1976). Consequently the drag of the gliding swimmer was modified by acceleration, called reaction-acceleration-force (AR). The surrounding water is also set in motion by the body movement relatively to the water which requires imparting momentum to displace the water in the body’s path (Ungerechts 2003). The momentum change of the water masses can be observed as sloshing water if a swimmer has touched the wall at the end of a race and a little bit later waters sloshes on the wall. The water masses which were moved once by the body by frictional effects develop an independent way of motion if the bodies are slowing down e.g. due to gliding phase. Due to inertia of these moved water masses act as flywheel masses and continues to accelerate the body. It is to be expected that a gliding person glides by effect of the ostensible additional masses differently compared to the easy acceptance that a steady and constant speed works. The purpose of this paper is to show a means to estimate AR by quantifying ‘added mass’.

Theoretical aspects

A swimmer in prone horizontal position when accelerated by a falling mass via a non-elastic cable from rest over a distance of several body lengths generates accelerated flow phenomena accompanied by (changing) interaction effects, called \( F_{\text{reak}} \). The reactive forces \( F_{\text{reak}} \) effect the motion of the centre of body mass which mentally could be separated in propulsive and resistive effects (but experimentally they cannot be measured separately). It is of major concern that \( F_{\text{reak}} \) can be considered as a sum of flow effects based on steady and unsteady components, respectively. This means the conditions \( a = 0 \) und \( a \neq 0 \) can be treated mathematically (under consideration of the actual speed values).

According to the mechanical law of motion under consideration of d’Alembert Principle the motion of a body is represented by equilibrium of external forces which when applied to aquatic activities means

\[
F_{\text{reak}}(t) - m*a(t) = 0
\]  

(1)

\( F_{\text{reak}}(t) \): time-depending reactive forces acting between swimmer and water mass

\( m \): mass of the swimmer

\( a(t) \): time-depending acceleration (positive, in swimming direction)
Each reactive force \( F_{\text{reak}} \) can be differentiated (in swimming direction). According to the 3rd Newton’s law of motion Cureton (1971) established

\[
F_{\text{reak}}(t) = F_{\text{prop}}(t) - F_{\text{resist}}(t)
\]  

(2)

It is reasonable to express the resistive term \( F_{\text{resist}}(t) \) by the steady component using the actual speed \( u \) as a basis und the unsteady term by using the dominating acceleration, it follows

\[
F_{\text{resist}}(t) = D*u^2(t) + \Delta m*a(t)
\]  

(3)

\( D: \) constant steady factor of drag, unit = kg/m and \( \Delta m: \) factor of proportionality, unit = kg

The factor of proportionality of the acceleration-reaction-force, called virtual hydrodynamic mass \((\Delta m)\) or ‘added mass’ can be derived from theoretical hydrodynamics. Positive or negative acceleration of a body will be transferred to fluid surrounding resulting in acceleration-reaction-force (AR). AR is proportional to acceleration a while \((\Delta m)\) represents the non-steady factor of proportionality. \( \Delta m \) can be quantified. Accelerated water mass act like ‘added mass’ which augments virtually the body mass representing a more inert body. Combining equation (3) and (1) gives

\[
(F_{\text{prop}}(t) - D*u^2(t)) \div a(t) = \Delta m
\]  

(5)

The following variables were deduced per swimmer experimentally:

a) \( u = \) actual speed  
b) \( a = \) non-steady acceleration  
and  
c) \( F_{\text{prop}}(t) \)

Equation (5) is valid under the condition that the relationship \( \Delta m*a(t) \) is linearly dependent on the acceleration; in case if, the hypothesis is true that virtual added mass effects due to non-steady flow are existent in real fluids.

**Methods**

15 elite swimmers (10 males, 5 females), aged 22 – 26 years were towed in prone body position by means of a Semi-Tethered-Machine (STM) over a distance of 50 m next to the waterline (Wirtz 1996). The towing force of STM produced by the means of falling load was transferred to the swimmers via a non-elastic cable. The falling load produced via a pulley-system a towing force accelerating the swimmer. The swimmer were asked: in prone position, both hands stretched out holding grip at the end of non-elastic rope, hold breath, head between upper arms, keep body tension until end of towing. An appropriate order of wheels enabled the registration of time-depending velocity data via electro-optical detection (Fig. 1).
Figure 1  Semi-Tethered-Machine (STM), large wheel for swimmers’ rope, small wheel for a load’s rope

The data of the swimmers’ change of velocity were taken for further procedures in different steps:

1. Approximation-polynomial-calculation, velocity over time (a polynomial 6th grade results in stable values concerning the relevant temporal interval in which the velocity changes)

2. Calculation of the acceleration-function via differentiation of the Approximation-polynomial (here at six different)

3. Calculation of discrete value of the speed $u$ at each time-instances (when towing force and resistive flow effects are balancing each other, acceleration is zero)

4. Calculation of the steady component, representing the steady part of drag forces, using speed data (III.) after determination of the individual factor of resistance $D$ (see below)

5. Calculation of the un-steady component, representing the un-steady part of drag forces, using acceleration-data (II.) and equation (3)

6. Calculation of the difference between the steady and un-steady component of drag forces and check the linearity of that difference using a graph $\Delta$ (drag forces) over acceleration

7. Calculation of added mass $\Delta m$ which is the slope of the (checked) linear function.

Determination of the individual ‘steady factor of drag’ $D$

1. determination of $u$ = constant at speed in the steady period (Fig 2), e.g. $u = 1,65$ m/s

2. calculation of $D$: towing force/$u^2$

   $D = \frac{100}{1,925^2}$ (kg m/s$^2$)/(m$^2$/s$^2$) = 27,0 kg/m

**Results**

The steps yielding in $\Delta m$ will be exemplified for a case of one swimmer. In Fig. 2 speed-time-curve is shown (solid line: raw data) as well as the speed based on the approximation-polynomial 6th grade (broken line).
Figure 2 Speed-time curves of one towed swimmer (SMO) accelerated by STM from rest; the curves show a non-steady period and the beginning of the steady period; during the non-steady period the experimental curve is fitted by a polynomial equation of 6th grade.

As shown in Fig 2 the swimmers experience both components, first the non-steady and later the steady one. At small speed the acceleration is large and when speed increases acceleration impact decreases; just after the start a swimmer experience changes of speed decreasing by and by until after about 6.5 s the speed becomes constant (effects of towing and drag are balancing each other).

Figure 3 Force [N] depending on actual speed data; solid line: experimental data, broken line: constant speed and no acceleration.

Next the non-steady component of reactive forces $F_{\text{resist}}(t)$ is calculated as follows: estimation of the acceleration via differentiation of the approximation-function at (here) 6 different time instants which represents the change of motion of the falling mass considering the effects of the mechanical properties of the STM (Klauck 1999). After the velocity is determined at the same 6 time instants the steady component of $F_{\text{resist}}(t)$ is calculated using a realistic $D = 27$ kg/m. Both approaches result in two force-time curves (Fig. 3). The difference of these curves is remarkably at slow actual speeds and at higher speeds they merge. In the beginning higher accelerations influence the flow effects by added mass effects which vanish later. This development of the differences of the $F_{\text{resist}}(t)$ -components from the acceleration is represented in Fig. 4.
The Fig. 4 reveals that the dependency of the difference of (steady – non-steady) components on acceleration is linear. This allows for a) the application of equation (5) to calculate the factor of proportionality ($\Delta m$) of the acceleration-reaction-force and b) a justification of the assumption that the $F_{\text{res}}(t)$ can be distinguished in a steady and non-steady component like in equation (3); the data of $\Delta m$ for all 15 swimmers are listed in Tab. 1 (because of small number of subjects and partly large variation a statistical approach was not executed).

Table 1 Parameters of 15 swimmers accelerated from rest

<table>
<thead>
<tr>
<th>VPN</th>
<th>Body mass [kg]</th>
<th>Body length [m]</th>
<th>D [kg/m]</th>
<th>$\Delta m$ [kg]</th>
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<tr>
<td>M1</td>
<td>63,0</td>
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<td>36,0</td>
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<td>71,0</td>
<td>1,80</td>
<td>29,5</td>
<td>28,0</td>
</tr>
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</table>

$D$ = individual data of steady factor of drag, $\Delta m$ = added mass, representing the non-steady factor of proportionality of the acceleration-reaction-force.

In a speed corridor $u$ between 1.0 – 1.6 m/s the values of $\Delta m$ for these swimmers vary between 30 – 70 kg and those for the steady factor of drag $D$ vary between 22 – 38 kg/m. The magnitudes of $\Delta m$ are in the range of ‘added mass’ human swimmers are experiencing in daily life. Elite swimmers may experience acceleration over 0,5 – 0,6 s resulting in peak acceleration ranging from 6 – 8 m/s² (Ungerechts 1988) which results in values for $F_{\text{react}}$ on the basis of $+ \Delta m = 50$ kg, $a = 5$ m/s², $D = 27$ kg/m und $u = 1,925$ m/s as follows:

- **Acceleration-reaction-force AR:**
  
  $+ \Delta m \cdot a = 250$ N

- **Speed dependant resistive force:**
  
  $D \cdot u^2 = 100$ N

During self-induced propulsion a swimmer takes advantage from the power transfer of nearly all muscles and with no doubt he/she will overcome 350 N easily (under gravity condition humans produce much higher forces to move at $a = 5$ m/s²).
**Discussion**

The consideration of non-steady flow effects is essential when calculating mechanical work or efficiency of self-induced propulsion at a given physical competence. This study using a test closely related to natural swimmers situation (surfing at water level). Caspersen et al. (2010) used an oscillating 2.8 m long bar with handles and with springs, while researching the relative added mass ($M_a\%$) for boys, women and men and concluded that the added mass in human swimmers, in extended gliding position, is approximately 1/4 of the subjects’ body mass. A direct comparison to the results of this study concentrating on the effects when the acceleration is positive is not possible. Since during cyclic activities in aquatic space deceleration also occurs the magnitude of ‘added mass’ is expected to be different because of different flow events. The mathematical treatment is still a challenge for experts to approach a more accurate model of flow effects due to cyclic interaction of human body and displaced water mass.

**Literature**


**Inter-individual variability of body angles during swim start: analysis of preferential and non-preferential techniques for expert swimmers**

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**Keywords**: biomechanics, variability, expertise, preferential technique, swimming start

**Introduction**

Most of the biomechanical studies of start time have used kinetic and kinematical analyses to compare the two main start techniques used in competition: the grab and the track starts. Using a track start, swimmers tend to leave the block quicker (Ayalon, Van Gheluwe & Kanitz 1975) and to
make a flatter flight trajectory due to higher horizontal velocity (Costill, Maglischo & Richardson 1992). With the grab start, swimmers spend more time on the block (Issurin & Verbitsky 2003). The above-referred studies, as many other studies, tried to observe which is the best starting technique to increase performance. Indeed, studies that compared the two start techniques showed the comparison between grab starters and track starters, each swimmer in his preferential technique. These studies were particularly interested in the starting technique effect. However, studies that analyzed differences between start techniques and that take in consideration the swimmers start preference are scarce as Vilas-Boas et al. showed us (2003) or more recently with Vantorre et al. (2011) on angular momentum. Knowing that the use of preferential technique may induce better performance to 15m, as well as other differences like a higher variability in some parts of the movement. Indeed, some studies showed that expert swimmers were able to exploit movement variability to achieve the dual-task goal of the swimming start: dive as far as possible to minimise resistances and to make a forward rotation to enter into the water properly (Seifert et al. 2010; Vantorre, Seifert, Fernandes, Vilas-Boas & Chollet 2010). Consequently, it is challenging to investigate the impact of the non-preferential technique in comparison to the preference one.

The aim of this study was to analyse inter-individual variability on body angles and velocity between preferential and non-preferential start techniques during aerial phase of swim start.

**Method**

Five expert swimmers (age: 23.2 ± 1.5 years, size: 1.8 ± 0.1 m, weight 78.6 ± 8.2 kg) male sprinters specialists of freestyle voluntarily participated in this study. The skill level was expressed in percentage of the world record time (% of RM) for a 100-m crawl in 50-m pool and was 89.3 ± 3.0%. The target time was expected to be within more or less 2.5% of the race time. In a 25m swimming pool, each swimmer performed six randomised 25m front crawl at the 50m race pace, being three repetitions using the track start and three using the grab start techniques. Grab start technique was their preferential technique.

**Kinematics**

Three cameras (two above water and one underwater) with rapid shutter speed (1/1000 s) were used to follow the swimmer from the block to the entry of the feet in the water. The first camera (50 Hz, Sony® DCR-HC42E) was placed from the edge of the pool and videotaped the leave block and flight phases. Two other cameras (50Hz, JVC GR-SX1 SVHS-C PAL) were mounted on a specially designed support placed at the lateral wall 3m from the edge of pool deck (one 30cm above and the other 30cm under the water surface), videotaping the entry phase. A fourth camera was placed in front of the 15-m mark and videotaped the swimmer from the moment when the head broke the surface of the water to the end of the 15-m. Kinematical analysis was processed using APAS (Ariel Performance Analysis System, Ariel Dynamics Inc. 2001). The spatial model was composed by 20 anatomical landmarks digitalised in each frame, defining 14 body segments model (De Leva 1996). Images, once digitised, allowed us to obtain the instantaneous velocity of the center of gravity of the swimmer throughout the movement and limbs angles. Concerning limbs organisation of the swimmer during the different phases of the movement, a recalculation of the center of gravity of the arms and of the legs allowed us to summarise a segment in a point using Matlab (Matlab 7.1, Mathworks Inc 2012). Indeed, angles were calculated for the arm between the center of gravity (CG) of the upper limb parts (hand, forearm and arm) and the trunk (CG arm – trunk) and concerning legs between the center of gravity of the lower limbs (foot, leg and thigh) and trunk (CG leg – trunk). These measurements were determined on all the movement from start signal and feet entry in the water. To compare the trials, trials were normalised on one hundred values.

**Inter-individual variability**

Concerning inter-individual variability, the temporal dynamics of limbs angles and velocity of the center of gravity during movement were studied. From the fastest trial for each subject, its duration
was normalised in 100 points. The average standard deviation of each variable was calculated by averaging the 100 standard deviations calculated point by point by taking all the subjects. This represented an overall indicator of the inter-individual variability. After that, local indicators of inter-individual variability were calculated at four key points: (1) first measured value; (2) time when the feet left the block; (3) time when the hands enter into the water; (4) time when the feet enter into the water. To do that, the average of standard deviations was calculated based on the 5 values before and 5 values after each key point.

**Statistical analysis**

A normal distribution (Ryan Joiner test) and the homogeneity of variance (Bartlett test) were verified and authorised parametric statistics (Minitab 15.1.0.0, Minitab Inc. 2006). Two-way ANOVA’s (fixed factor: technique; random factor: subject) were applied for all parameters (angles, velocity of the center of gravity, standard deviations of these parameters) to analyze the differences between techniques. Statistics were performed on mean values but also on the average standard deviations (aSD). The significance level was set at p < .05.

**Results**

Means standard deviations were calculated for the angles and the velocity of the center of gravity. On these values, only the average standard deviation of the velocity of the center of gravity is significantly different between the two techniques (Table 1).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Experts</th>
<th>Non experts</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG Arm-Trunk 1 (°)</td>
<td>93.22 ± 10.12</td>
<td>108.24 ± 4.42 (a.b)</td>
</tr>
<tr>
<td>CG Leg-Trunk 1 (°)</td>
<td>30.09 ± 4.18</td>
<td>27.36 ± 5.22 (a)</td>
</tr>
<tr>
<td>InstV 1 (m.s⁻¹)</td>
<td>0.09 ± 0.09</td>
<td>0.05 ± 0.04</td>
</tr>
<tr>
<td>CG Arm-Trunk 2</td>
<td>40.70 ± 78.40</td>
<td>66.35 ± 99.29 (a.b)</td>
</tr>
<tr>
<td>CG Leg-Trunk 2</td>
<td>169.32 ± 10.20</td>
<td>167.62 ± 8.22</td>
</tr>
<tr>
<td>InstV 2</td>
<td>4.15 ± 0.24</td>
<td>4.12 ± 0.33</td>
</tr>
<tr>
<td>CG Arm-Trunk 3</td>
<td>173.16± 7.85</td>
<td>169.97 ± 8.07(a)</td>
</tr>
<tr>
<td>CG Leg-Trunk 3</td>
<td>152.15 ± 15.53</td>
<td>154±6.23(b)</td>
</tr>
<tr>
<td>InstV 3</td>
<td>4.99 ± 0.31</td>
<td>4.94± 0.25</td>
</tr>
<tr>
<td>CG Arm-Trunk 4</td>
<td>166.59 ± 16.49</td>
<td>170.24 ± 8.74(a,b)</td>
</tr>
<tr>
<td>CG Leg-Trunk 4</td>
<td>166.64 ± 6.15</td>
<td>166.4 ± 10.15(b)</td>
</tr>
<tr>
<td>InstV 4</td>
<td>3.94 ± 0.32</td>
<td>3.72 ± 0.38(a)</td>
</tr>
<tr>
<td>CG Arm Trunk aSD</td>
<td>29.02</td>
<td>34.15(a)</td>
</tr>
<tr>
<td>CG Leg-Trunk aSD</td>
<td>9.47</td>
<td>9.61</td>
</tr>
<tr>
<td>InstV mSD</td>
<td>0.27</td>
<td>0.25</td>
</tr>
<tr>
<td>15-m Time</td>
<td>6.44 ± 0.36</td>
<td>6.51 ± 0.32(a)</td>
</tr>
</tbody>
</table>

a: significant difference compared to preferential technique on averages, b: significant difference compared to preferential technique on standard deviations at p <0.05.

Curves and standard deviations of body angles and velocity of the CG during the aerial phase of the start were summarised in the following figure (Figure 1) with key points in bold.
A higher inter-individual variability of CG Arm-Trunk (29.02 vs 34.15 for average standard deviations) and no significant difference at hand entry showed an adaptation to the task of starting in the two techniques by the expert swimmers (Vantorre, Seifert, Fernandes, Vilas Boas et al. 2010). However, lower alignment of upper limb (lower CG Arm-Trunk angle) during its entry induced a lower efficiency at entry confirmed with a higher decrease in velocity (Seifert et al. 2010). Concerning CG Leg-Trunk, experts had significant higher variability at arms entry (with 15.53 versus 6.23 respectively for expert and non-expert swimmers) but results were inverted at feet entry (with 6.15 versus 10.15 respectively for expert and non-expert swimmers) showing a process of adaptation during the transition between rotating in the air and enter in the water in a streamlined position. Results also showed a use of various body angles—especially in preferential technique—in the aerial phases (as previously showed by Seifert et al. 2010) suggesting that several behavioural profiles enable to reach effectively the task-goal.

**Conclusion**

These results were fundamental to link with the study of the same technique done on a traditional block versus the OSB11 starting block (Honda, Sinclair, Mason & Pease 2012; Takeda, Takagi & Tsubakimoto 2012). Indeed, this study showed the interest of considering movement variability as a way of individualisation and exploration during the training process, suggesting that movement variability could be viewed as functional and adaptive. One promising way could be to examine the adaptation of swimmers on the new blocks.

**References**


3 Coaching

*Multidimensional connection between dry-land and in-water physical fitness in water polo players aged up to 14 years*

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**Keywords:** water polo, training process, testing

Water polo players realise their process in water, as basic training, and as dry-land exercises, as additional training. As both training forms must be functionally and logically connected wholes, this paper is aimed at determining the relation of dry-land and in-water physical fitness in water polo players aged up to 14 years. The quantitative type of research included a sample of respondents consisting of 42 randomly chosen water polo players from the Republic of Serbia (average age 13.2±0.5 years, BH = 171.77±7.98 cm, BM = 63.51±8.04 kg, and length of training 4.36±1.43 years). The players were tested for general dry-land physical fitness (long jump; 10s push-ups; 30s sit-ups; flexibility sit and reach test) and test battery indicating general physical fitness in pool (15m crawl; 25m crawl; 50m crawl; 200m crawl; 25m legs crawl kick; 25m breaststroke kick; 25m egg beater kick; 25m with head up; 25m swimming with the ball). The results are analysed by descriptive analysis, followed by multidimensional scoring transformation into the scores of general fitness of players in water and dry. By applying linear regression analysis the level of connection between the observed variables of general dry-land and in-water physical fitness was established. The results have shown that the connection of general scores of dry-land and in-water physical fitness in water polo players aged up to 14 years is on the level of 20.4% (AdjR² = 0.204) and is statistically significant on the level F=11.56, p=0.002. Based on the obtained results it can be concluded that it is of utmost importance that the training process of water polo players aged 14 years is performed parallel both in water and out of the pool because this way more efficient positive transfer of mutual physical fitness of the players is in focus.

**Introduction**

Long-term training process implies different forms of work directed at achievement of maximum sport results. The athletes need to undergo all training phases, from general preparation to narrow specialised ones. The coach’s task in the long-term training process is to permanently supervise the athletes’ progress, which implies a periodical conduction of testing of physical abilities. For a water polo player to compete in the senior competition, several years of training work are required so that they might master the physical and technical-tactical demands of the water polo game. It is especially important to observe, in the early phase of the sport development, the rules of the training process in order to meet the terms for achievement of maximum results. As in other sport disciplines, in water polo, too, the training process is a complex one, and especially the training with water polo players up to the age of 14 years who biologically are in the phase of a vigorous development, and with regard to training in the phase of initial specialisation. The training is based on the general physical preparation through various forms of training work, directed to the athlete’s preparation for specific forms of training work. Water polo players realise their process in water, as basic training, with dry-land exercises as additional training. Both training forms are important and have their targets and tasks aimed at sports-training development of water polo players especially for junior players. The question is how much dry-land training influences the improvement of the general physical preparation of players in the water. As both training forms must be functionally and logically connected wholes, this
paper is aimed at determining the relation of dry-land and in-water physical fitness in water polo players aged up to 14 years.

**Method**

The quantitative type of research included a sample of respondents consisting of 42 selected water polo players from 19 Serbian water polo clubs with average age 13.2±0.5 years, average height BH=171.77±7.98 cm, average weight BM=63.51±8.04 kg, and length of training 4.36±1.43 years. The players were tested for general dry-land physical fitness and test battery indicating general physical fitness in pool. Tests were carried out in water in the pool size of 50×25m, while the motor measurements were carried out in a dry hall of the Institute for Sports Medicine.

For the checking of the swimming fitness of respondents in the water, standardised tests were used (Dopsaj & Bratusa 2003) for age between 12 and 14 years.

The following tests were done in the water:
- crawl 15, 25, 50 and 200m (W_c15m, W_c25m, W_c50m, W_c200m)
- 25m crawl with head up (W_c25mH)
- 25m crawl with ball (W_c25mB)
- Specific swimming by using legs 25m, crawl kick, breast kick and egg biter kick (W_ck25m, W_bk25m, W_ebk25m)

The following tests were done on the land:
- Seat-ups (D_s-ups)
- Long jump (D_l-jump)
- Push ups (D_p-ups)
- Flexibility-bench sit and reach (D_flexibility)

**Variables**

Each of the above tests is one variable and another two variables were deduced:
- General score of physical fitness in water (W_score)
- General score of physical fitness on dry land (D_score)

**Statistical analysis**

According to this, we got the overall of 15 variables and the results are analysed by descriptive analysis, followed by multidimensional scoring transformation into the scores of general fitness of players in water and dry. By applying linear regression analysis the level of connection between the observed variables of general dry-land and in-water physical fitness was established.

**Results**

Table 1 shows the basic descriptive statistics of tested variables. The results of variation coefficients (cV%) are within the range from 6.41% for the variable W_c200m to 33.33% for the variable D_score.
Table 1  Descriptive statistic

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>SD</th>
<th>cV%</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>W_c15m (s)</td>
<td>8.17</td>
<td>0.70</td>
<td>8.59</td>
<td>6.46</td>
<td>9.55</td>
</tr>
<tr>
<td>W_c25m (s)</td>
<td>14.79</td>
<td>1.09</td>
<td>7.35</td>
<td>13.08</td>
<td>17.02</td>
</tr>
<tr>
<td>W_c50m (s)</td>
<td>31.91</td>
<td>2.14</td>
<td>6.70</td>
<td>27.23</td>
<td>36.70</td>
</tr>
<tr>
<td>W_c200m (s)</td>
<td>160.66</td>
<td>10.29</td>
<td>6.41</td>
<td>139.00</td>
<td>185.26</td>
</tr>
<tr>
<td>W_c25mH (s)</td>
<td>15.08</td>
<td>1.02</td>
<td>6.73</td>
<td>13.36</td>
<td>17.57</td>
</tr>
<tr>
<td>W_c25mB (s)</td>
<td>15.93</td>
<td>1.21</td>
<td>7.61</td>
<td>13.84</td>
<td>19.87</td>
</tr>
<tr>
<td>W_ck25m (s)</td>
<td>25.87</td>
<td>2.34</td>
<td>9.05</td>
<td>21.80</td>
<td>31.16</td>
</tr>
<tr>
<td>W_bk25m (s)</td>
<td>26.38</td>
<td>2.06</td>
<td>7.82</td>
<td>23.29</td>
<td>33.03</td>
</tr>
<tr>
<td>W_ebk25m (s)</td>
<td>30.22</td>
<td>2.90</td>
<td>9.61</td>
<td>25.03</td>
<td>38.77</td>
</tr>
<tr>
<td>W_score (points)</td>
<td>14.58</td>
<td>24.71</td>
<td>169.46</td>
<td>-45.04</td>
<td>55.28</td>
</tr>
<tr>
<td>D_l-jump (cm)</td>
<td>183.00</td>
<td>25.21</td>
<td>13.78</td>
<td>137.00</td>
<td>230.00</td>
</tr>
<tr>
<td>D_s-ups (repetition)</td>
<td>20.55</td>
<td>3.37</td>
<td>16.38</td>
<td>14.00</td>
<td>25.00</td>
</tr>
<tr>
<td>D_flexibility (cm)</td>
<td>4.05</td>
<td>6.58</td>
<td>162.64</td>
<td>-15.00</td>
<td>18.50</td>
</tr>
<tr>
<td>D_p-ups (repetition)</td>
<td>4.29</td>
<td>3.90</td>
<td>91.07</td>
<td>0.00</td>
<td>10.00</td>
</tr>
<tr>
<td>D_score (point)</td>
<td>50.00</td>
<td>16.67</td>
<td>33.33</td>
<td>18.99</td>
<td>85.84</td>
</tr>
</tbody>
</table>

The variation coefficient (cV%) for the variables W_score, W_flexibility and D_p-ups is above 30%.

Table 2 shows the results of a linear regression analysis which show that on the level of 20.4% there is a connection of observed variables on dry-land and in-water, and table 3. shows that the connection is important on the level p=0.002.

Table 2  Linear regression analysis—model summary

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.474</td>
<td>.224</td>
<td>.205</td>
<td>14.86155</td>
</tr>
</tbody>
</table>

Table 3  Linear regression analysis ANOVAb

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>2554.105</td>
<td>1</td>
<td>2554.105</td>
<td>11.564</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>8834.621</td>
<td>40</td>
<td>220.866</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>11388.726</td>
<td>41</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Diagram 1 shows the connection of observed variables in-water and dry-land.
Diagram 1   Diagram of the linear regression analysis

**Discussion**

The results of the descriptive analysis show that the variation coefficient with most variables is within limits below 30% (D_score CV%=33.33, which is the limit value), which shows us that the obtained results are uniform in relation to average values, i.e. that the given variables are homogenous. Three variables stand out as inhomogeneous: variable W_score CV%=169.45, variable D_flexibility CV%=162.64, variable D_p-ups CV%=91.07. One of the reasons for the distinct deviation from average values of the variable W_score is probably the big number of children from various clubs who do not train always on the adequate level, i.e. according to standards and recommendations for the given age. Although all observed variables in the water are within the limits of the natural variability, as a summary, major deviations from the average have occurred, which is shown by the variable W_score (MIN=45.04 score; MAX=55.28 score). Major deviations of the variables D_p-ups (MIN=0 repetitions; MAX=10 repetitions) and D_Flexibility (MIN=-15cm; MAX=18.5cm) are probably the consequence of lack of uniform training work on dry land which is implemented in various clubs. Single respondents did not manage to meet the criteria of these tests so that it can be assumed that the basic cause is the insufficient i.e. inadequate training work on dry land in the club. Observing all the results it can be seen that the results of the observed single variables in the water are extraordinary homogenous (variation coefficient (CV%) ranges from 6.41% for the variable W_c200m to 9.61% for the variable W_ebk25m) of the observed variables on dry land (the variation coefficient (CV%) ranges from 13.78% for the variable D_l-jump to 162.64% for D_flexibility). The obtained results show that the emphasis of the training work, generally on the representative sample of water polo players aged up to 14
years, is directed to the water, whereas other forms of training work i.e. training work on dry land have been neglected.

The results of the linear regression analysis show that there is a connection between the tests on dry land and in the water which describe the general physical fitness of players aged up to 14 years. The connection of observed variables of general scores of physical fitness on dry land and in the water \( p=0.002 \) shows the need for water polo players to perform the training process on dry land, too. The variable \( D \text{score} \) on the level 20\% explains the variable \( W \text{score} \) which shows that there is a positive transfer of the general physical fitness on dry land to the physical fitness in the water. However, although it can be said that 1/5 of the physical fitness on dry land influences the fitness in the water, the rest of the unexplained variability of 4/5 (almost 80\%) clearly shows that from the methodological point of view it can be asserted that it is extremely important for the goals of training work in the water (as the basic training) and on dry land (as additional training) to be specially defined (as the work in one environment does not automatically cover the work in the other environment). Also, the mentioned unexplained variability also hints at the extraordinary importance of training on dry land, as additional training in water polo, in the sense of development of physical capacities, already with players aged 14 years.

**Conclusion**

Based on the obtained results it can be concluded that it is of utmost importance that the training process of water polo players aged 14 years is performed parallel both in water and out of the pool because this way more efficient positive transfer of mutual physical fitness of the players is in focus. Although the results indicate this positive connection of fitness in two different environments (water and dry land) only 1/5, the remaining 80\% of independence indicates the inevitability of both training methods, structurally and functionally connected so that they develop all physical features, which is particularly important for regular sports-competitive development of junior water polo players.

The significance of this research is to hint that the general physical preparation should be complex, i.e. that in this age, although water polo players gradually enter a specialisation, the diverse approach to general preparation must not be neglected so that talented players could reach maximum sports achievements, in order to avoid that due to methodological deficit in the training process young players finish their career prematurely before they become seniors.

Future research should be directed to a larger number of young age categories and it should include a larger number of tests on dry land so that the results could be comparable and more representative.

**References**


**A simple field test for the assessment of aerobic swimming fitness: a multidimensional approach**

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**Keywords:** elite swimmers, field test, aerobic, lactate

**Introduction**

From the viewpoint of kinematics, swimming is a cyclical sport, while in terms of energy system loads, it predominantly belongs to endurance sports (Maglischo 2003). The aerobic energy system is basic for the support of a wide range of endurance effort in sport. Both in training and competition, swimmers will benefit from a well-developed aerobic energy system regardless of the type of performance required in sprint, middle distance or long distance swimming (Olbrecht 2000).

The training process involves many years of continuous and systematic work, which comprises a time cycle with different training methods and goals at which training regimes are aimed. However, during a given period of the training cycle, the coach must have a method or methods that are objective and easy to apply in order to control the competitive level of important physical abilities of swimmers, including the capacity of the aerobic energy system, i.e. of endurance fitness.

It is well known that blood lactate concentrations are the best indicators of the achieved swimming intensity (Olbrecht 2000). Also, lactate testing has already been used in the process of training optimisation, as increasing the concentration of lactate in the blood is the main metabolic mechanism responsible for the appearance of fatigue in swimmers during the training sessions or in the race. As the process of training is aimed to improve the swimmer’s results, that is, to increase the swimming velocity in the race, this implies that the ratio between swimming velocity and the achieved lactate concentrations can provide a basic two dimensional (2D) model useful for the coach in the objective control of the training process and the assessment of actual adaptation levels in swimmers.

The aim of this research was to define the generic model for a simple, valid and user-friendly field test for the coach to assess the levels of actual general aerobic fitness independent of the type of the swimmer (sprint, middle or long distance), which would be conducted by using only two variables: the swimming velocity and the lactate concentration levels.

**Method**

The sample consisted of 16 elite swimmers from different European countries (Serbia, Russia, and Bosnia and Herzegovina), with the freestyle as their main or first additional technique (10 males, age = 22.3 ± 3.9 yrs, FINA 2013 score = 801 ± 56; and 6 females, age = 19.1 ± 2.6, FINA 2013 score = 707 ± 59). Throughout the annual preparation cycle, all respondents swam the one aerobic load swim set: 12 x 100 m test in the regime of 1:30 min:sec, using the crawl stroke in a 50m pool. The test represented the hypothetical model simulation of aerobic energetic system stress. All subjects had the task to swim at the constant self-paced velocity to their maximum aerobic effort for a given test series.

All sets of the test series were measured chronometrically by the same investigator. On completion of the full test set, after 60 seconds of recovery, capillary blood from the finger was sampled to determine lactate concentrations (NOVA Lactate Plus, USA).

All the variables were subjected to a descriptive statistical analysis, linear regression and multivariate scoring analysis (Hair et al. 1998). Raw results were processed by the use of descriptive statistical analysis in order to calculate the basic descriptive statistics (MEAN – mean value, SD – standard deviation, cV% – coefficient of variation, Min – minimal variable value, Max – maximum variable value).
Multivariate scoring was applied to the results of the average swimming tempo in a series and of lactate concentrations in order to define the two-dimensional specification equation as the mathematical model for the assessment of aerobic swimming fitness. The level of aerobic fitness was expressed numerically, using the score scale between 0 and 100 points as the hypothetical minimum and maximum (Williams et al. 2008; Dopsaj et al. 2012). All statistical operations were carried out in Microsoft * Office Excel 2007 and the SPSS for Windows, Release 17.0 (Copyright © SPSS Inc. 1989–2002).

**Results**

The 12 x 100m/1:30 swimming set results are shown in Table 1. The results for all swim sets are shown in Figures 1 and 2 for males and females, respectively. Upper and lower limits as the criteria for the unacceptable and the excellent swimming tempo are also shown in Figures 1 and 2. Figure 3 presents 12 x 100m/1:30 swimming set results of S.F., a freestyle sprint specialist, during 14 months of training.

Table 1  
*The descriptive results for the 12 x 100m/1:30 swim set for the tested sample*

<table>
<thead>
<tr>
<th>Set Time Swim Tempo</th>
<th>Set Lactate Concentration in 1min rest</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MEAN ± SD (s)</strong></td>
<td><strong>cV%</strong></td>
</tr>
<tr>
<td>Males</td>
<td>67.97 ± 1.86</td>
</tr>
<tr>
<td>Females</td>
<td>72.01 ± 1.35</td>
</tr>
</tbody>
</table>

The results indicated that the average aerobic model sets of the swimming tempo were: Males = 67.97±1.86 s, with lactate concentrations after 60 s of recovery at the level of 7.11±2.18 mmol/L; and Females = 72.01±1.35 s, with lactate concentrations after 60 s of recovery at the level of 7.63±2.86 mmol/L. The coefficient of variation showed that all swim tempo results had a very low level of variation, which indicates that the tested swimmers were homogeneous across fitness levels (cV% 1.86 and 1.88% for males and females, respectively, Table 1). However, lactate concentrations were at the border of homogeneity range (above 30.0%). This was expected considering the fact that the tested groups were relatively small and the swimmers were of different types (sprint, middle or long distance).
Figure 2 The result model for the 12 x 100m/1:30 swim set for female swimmers

Figure 3 The results of S.F., a freestyle sprint specialist, during 14 months of training

The regression ANOVA showed that the defined two-dimensional mathematical equations for the assessment of aerobic swimming fitness (in Score numbers) for male swimmers were highly statistically significant at p value = 0.000, F relation = 9956170.0, and with Adj. \( R^2 = 1.00 \) (100% of explained common variance), with the following model:

Males: \( y = 381.4721448 - (\text{Set mean time (s)} \cdot 4.4720657) - (\text{La after 60s of recovery} \cdot 3.8145354) \);

The regression ANOVA showed that the defined two-dimensional mathematical equations for the assessment of aerobic swimming fitness (in Score numbers) for female swimmers were also highly statistically significant at p value = 0.000, F relation = 269909.0, and with Adj. \( R^2 = 1.00 \) (100% of explained common variance), with the following model:

Females: \( y = 515.3176492 - (\text{Set mean time (s)} \cdot 6.1531918) - (\text{La after 60s of recovery} \cdot 2.9132365) \).

**Discussion**

Every particular distance in swimming has its own specific training methods. A long-distance swimmer’s training will be different from that of a sprinter swimmer’s. Nevertheless, in all types of swimmers, the work on the aerobic endurance capacity and the aerobic power ability should aim to
improve the oxygen system, i.e. the aerobic capacity, or to minimise the lactate production for a particular swimming velocity. In other words, the optimal training should take place at a workout intensity that maximally activates the complete energy system necessary to maintain a competitive distance or the training load (Olbrecht 2000; Janssen 2001).

It is well known that training intensity is essential for reaching the maximum competitive performance, which implies that the training program should be continually evaluated and adjusted according to the athlete’s/swimmer’s adaptive ability.

In relation to the need for predefined and precise control over the effects of the applied swimming training program, coaches should have access to easy-to-apply tools for tracking the direction and intensity of swimmers’ dominant physical and physiological adaptation. Adaptation mechanisms can be successfully employed through the improved energy efficiency or mechanical efficiency of swimming. In other words, the swimmer can achieve better results by swimming at the same intensity with lower metabolic reactions (lower lactate concentrations than in the previous cycle at the same swim intensity), or by maintaining equal metabolic reactions (the same lactate concentrations as in the previous cycle) at a more intense tempo of swimming. Of course, the most desirable model of adaptation is achieved if the swimmer can swim at a faster tempo and have lower lactate concentrations.

The results of this study showed that the precision of estimation of the obtained mathematical models for assessing aerobic swimming fitness, in the form of a cybernetic 2D model, is absolute. In addition, they have acceptable sensitivity to determining the level of change at the assessed aerobic ability in relation to the annual training cycle (Figure 3, test 20.01.2011, Mean set swim time 1:09.91, 60 s rest lactate level = 7.3, Aerobic set score = 40.78 units; test 05.01.2012, Mean set swim time 1:07.62, 60 s rest lactate level = 6.3, Aerobic set score = 55.82 units; improvement after 12 months of training: 3.28% faster swimming, according to Mean set swim time; 13.70% efficient metabolic rate, according to 60 s rest lactate level; and 36.88% better aerobic fitness, according to Aerobic fitness level score number).

Thus, the application of the defined equation model could provide better management and definite positive effects on increasing the efficiency of the training process in swimming (Olbrecht 2000; Janssen 2001; Williams et al. 2008).

Conclusions

The results showed that it was possible to define a mathematical model for a practical field test to be used in managing the training process with regard to aerobic fitness level assessment. This provides a practical tool that can enable coaches to control the efficiency of the applied training model with more accuracy, by assessing the adaptation of swimmers in terms of aerobic fitness. In the future studies it would be necessary to define the same models in relation to the type of swimmers (sprint, middle or long distance) and to different age groups.

References

Performance analysis of elite female water polo teams in the 2013 World Championships

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¹Kamakura Women’s University, Japan

Keywords: water polo, notational analysis, competition, topnotch team, ball game

Abstract
This study compares the performance characteristics of the high- and low-ranking teams in the female water polo tournament at the 2013 FINA World Championships. Data on 2,500 shots and 682 exclusion fouls were obtained from official score sheets, which were provided by the organising committee of the FINA World Championships. Performance variables were defined as follows: number of shots and goals by style (center, action, 5-m, counter-attack, exclusion, or penalty), shot results (goal scored or goal saved by goalkeeper [GK]), exclusion fouls (in field or in center), goal percentages, and percentage of GK saves for each style of shot. The frequency of the performance variables, both in offense and defense, were calculated per match. The sixteen participating teams were divided into four groups based on their final rankings in the championships as follows: 1st- to 4th-place teams (G1), 5th- to 8th-place teams (G2), 9th- to 12th-place teams (G3), and 13th- to 16th-place teams (G4). In terms of offense, G1 had significantly higher frequencies, compared to the other groups, of counter-attack shots and counter-attack goals. G4 had significantly lower frequencies, compared to the other groups, of total shots and action goals. As for defense characteristics, G1 showed significantly lower frequencies of action shots, total shots, and GK saves in counter attacks. G4 showed significantly higher frequencies of counter-attack shots, action goals, center goals, and GK saves.

Introduction
Water polo is the oldest ball game in the modern Olympic Games, and it was adopted at the Paris Games in 1900. FINA, the international organisation of water sports (including water polo), launched the World Championships for men’s water polo in 1973 and the World Championships for women’s water polo in 1986. In this tournament, which is held every two years, sixteen men’s teams and sixteen women’s teams, in which every continent is represented, compete in a round-robin preliminary round and a knock-out elimination round over the course of two weeks.

Match-analysis research is performed to provide detailed feedback on the teams’ and players’ performances during a particular match and throughout the tournament [Argudo et al. (2011), Escalante et al. (2013)]. Takagi et al. (2005) developed a database system and conducted principal-component analysis to investigate the relationship between game performance and the skill components of world-class water polo players at the 2001 World Championships. Argudo et al. (2008) defined fourteen shooting situations that occur during a match and calculated the efficacy value of each situation for the participating teams in order to compare the differences between the winning team and the losing teams at the 2003 World Championships. Lupo et al. (2010) showed that competition level has a relevant impact on the occurrence of technical and tactical indicators especially in relation to even, counter-attack, and power-play situations. This report suggested that counter attacks were more frequent in low-level competitions and that a higher number of power plays occurred in high-level competitions. Escalante et al. (2012) found that in the semifinal, bronze-, and gold-medal phase, goalkeeping ability was the only aspect that differentiated between winning and losing teams in the international female water polo tournament. Lupo et al. (2014) emphasised that water polo coaches must realise the importance of analyzing the differences in goals scored.
because there are many factors that determine whether a water polo game is lost by a slim margin or by a wide margin.

The majority of the above research focused on the tactical or technical differences between winning teams and losing teams. However, no previous studies have focused on analyzing the match performances based on teams’ final rankings in an international tournament. Thus, this study aims to compare the performance characteristics between high- and low-ranking teams in the female water polo tournament at the 2013 FINA World Championships.

**Method**

FINA provides the official scores of every international tournament (i.e., Olympic Games, World Championships, and European Championships) on the Omega Timing website. These scores include information on the number and style of shots, goals, and major fouls for each player and the official timing for each performance variable. This study obtained sample data covering 2,500 shots and 682 exclusion fouls at the 2013 World Championships female water polo tournament, which comprised forty-four matches. Performance variables were defined from the official scores as follows: number of shots and goals by style (center, action, 5-m, counter-attack, exclusion, or penalty), shot results (goal scored or goal saved by the goalkeeper [GK]), exclusion fouls (infield or center), goal percentages, and the percentage of GK saves for each style of shot. These variables are already in general use among water polo coaches and technicians [Escalente et al. (2012)]. Forty-one performance variables were related to defense and forty-one to offense, and the playing frequency and percentage of the performance variables in defense and offense were calculated per team, per match. The sixteen participating teams were divided into four groups based on their final rankings in the championships as follows: 1st- to 4th-place teams (G1), 5th- to 8th-place teams (G2), 9th- to 12th-place teams (G3), and 13th- to 16th-place teams (G4). The means and standard deviations of performance variables were calculated by ranking the groups in order to clarify the differences in performance variables between the groups. The Tukey HSD post-hoc test and either ANOVA or the Kruskal-Wallis test were applied as statistical processing tools. The accepted level of significance was set at 95% (p<0.05). All calculations were performed using the statistical package SPSS 21 (IBM).

**Results**

The means and standard deviations of frequency and percentage for each shot, goal, GK save, and exclusion foul, per match, are presented in Table 1 and Table 2. The means and standard deviations of frequency for each variable according to the classified four groups, per match, are presented in Tables 3, 4, and 5. The number of offense variables that statistically differentiated one group from the other groups were as follows: twenty-one variables for G1, eleven for G2, twelve for G3, and twenty-four for G4. The number of defense variables that statistically differentiated one group from the other groups were as follows: twenty-three for G1, thirteen for G2, ten for G3, and twenty-eight for G4. The total number of variables that statistically differentiated between adjacent groups were nine for G1 vs. G2, one for G2 vs. G3, and twelve for G3 vs. G4.

| Table 1. Frequency and percentage for shot variables in all female match of World Championships 2013. Data are means ± SD. |
|---|---|---|---|---|---|---|
|   | Center | Action | Sink | Counterattack | Exemplar | Penalty | Total |
| Shot | 3.6 ± 2.4 | 10.76 ± 2.2 | 6.3 ± 4.5 | 7.3 ± 3.8 | 4.0 ± 2.6 | 1.1 ± 1.4 | 28.4 ± 6.5 |
| Goal | 1.0 ± 1.0 | 0.8 ± 0.8 | 1.5 ± 1.5 | 0.8 ± 1.4 | 2.4 ± 1.7 | 0.8 ± 1.2 | 16.3 ± 5.3 |
| Goal percentage | 30.1 ± 30.0% | 27.5 ± 17.1% | 20.8 ± 18.9% | 65.2 ± 20.7% | 68.0 ± 25.6% | 77.8 ± 28.8% | 35.0 ± 12.1% |
| GK save | 1.2 ± 1.1 | 0.3 ± 2.0 | 2.0 ± 1.0 | 0.3 ± 0.6 | 1.0 ± 1.0 | 0.1 ± 0.5 | 7.3 ± 3.1 |
| GK save percentage | 31.2 ± 28.2% | 22.9 ± 19.8% | 27.2 ± 19.2% | 25.7 ± 17.3% | 22.1 ± 20.4% | 11.1 ± 29.0% | 26.9 ± 9.5% |

| Table 2. Frequency for exclusion variables in all female match of World Championships 2013. Data are means ± SD. |
|---|---|---|
|   | Center | Field | Total |
| Exclusion | 44.4 ± 2.8 | 33.3 ± 2.1 | 77.8 ± 3.3 |
Discussion

The purpose of this study was to compare the performance characteristics of high- and low-ranking teams in the female water polo tournament at the 2013 FINA World Championships.

In terms of offense characteristics, G1 showed a significantly higher frequency of counter-attack shots compared to the other groups (2.4±2.4 vs. 0.5±0.6, 0.8±1.1, 0.5±0.8) and counter-attack goals (1.7±2.0 vs. 0.3±0.5, 0.6±0.9, 0.3±0.6). G4 showed a significantly lower frequency of total shots compared to the other groups (20.9±5.4 vs. 29.9±5.8, 30.5±5.6, 29.6±4.5) and action goals (2.1±1.3 vs. 3.5±2.8, 4.5±2.9, 2.3±2.3). These results suggest that for a female water polo team to become top-tier, its members must have fast swimming speeds in order to outpace their opponents and display strong shooting abilities in international matches.

### Table 3. Frequency and percentage of shot and OK save variables for each group in offense. Data are means ± SD.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Center</th>
<th>Action</th>
<th>Sm</th>
<th>Counterattack</th>
<th>Counter</th>
<th>Efficiency</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>Goal</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>Percentage</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
</tbody>
</table>

### Table 4. Frequency and percentage of shot and OK save variables for each group in defense. Data are means ± SD.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Center</th>
<th>Action</th>
<th>Sm</th>
<th>Counterattack</th>
<th>Counter</th>
<th>Efficiency</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shot</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>Goal</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>Percentage</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
</tbody>
</table>

### Table 5. Frequency and percentage of action variables for each group in offense and defense. Data are means ± SD.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Center</th>
<th>Field</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>3.3 ± 1.3</td>
<td>8.0 ± 3.4</td>
<td>11.3 ± 4.7</td>
</tr>
<tr>
<td>G2</td>
<td>7.8 ± 2.5</td>
<td>1.8 ± 2.6</td>
<td>9.6 ± 4.2</td>
</tr>
<tr>
<td>G3</td>
<td>3.7 ± 2.2</td>
<td>0.3 ± 0.6</td>
<td>4.0 ± 2.8</td>
</tr>
<tr>
<td>G4</td>
<td>5.9 ± 2.1</td>
<td>0.8 ± 1.5</td>
<td>6.7 ± 2.6</td>
</tr>
</tbody>
</table>

### Table 6. Frequency and percentage of other action variables for each group in offense and defense. Data are means ± SD.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Center</th>
<th>Field</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>5.3 ± 2.0</td>
<td>3.5 ± 2.2</td>
<td>8.8 ± 4.3</td>
</tr>
<tr>
<td>G2</td>
<td>4.5 ± 2.2</td>
<td>2.9 ± 1.8</td>
<td>7.4 ± 3.8</td>
</tr>
<tr>
<td>G3</td>
<td>5.9 ± 2.5</td>
<td>4.1 ± 2.8</td>
<td>10.0 ± 4.3</td>
</tr>
<tr>
<td>G4</td>
<td>3.9 ± 2.4</td>
<td>3.2 ± 2.3</td>
<td>7.1 ± 2.8</td>
</tr>
</tbody>
</table>
As for defense characteristics, G1 showed a significantly lower frequency of action shots (7.4±3.6 vs. 12.0±4.9, 12.4±5.2, 12.9±5.4), total shots (24.1±5.7 vs. 28.5±5.0, 30.0±4.8, 34.1±6.5), and GK saves in counter attacks (0.6±0.9 vs. 0.1±0.3, 0.1±0.3, 0.1±0.3). G4 showed a significantly higher frequency of counter-attack shots (2.8±2.7 vs. 0.6±1.0, 0.8±1.2, 0.9±1.5), action goals (5.9±3.9 vs. 1.3±1.1, 3.7±1.9, 3.1±2.2), center goals (3.1±2.3 vs. 1.3±1.2, 1.0±1.2, 1.6±1.3), and a higher percentage of GK saves (20.5%±6.6% vs. 31.3%±9.6%, 28.1%±8.6%, 29.9%±10.1%). These results suggest that the higher-ranked teams have superior defensive ability in preventing an opponent’s shots. The results also suggest that lower-ranked teams need improvement in the following areas: increased swimming speed and anticipation of attack situations to prevent an opponent’s counter attack; strong center-back players to confront an opponent’s center player; and an increase in the GK’s ability to save shots.

Certain variables differed between two adjacent groups. Between G1 and G2, three offensive variables differed: action shots (10.4±4.7 vs. 14.2±4.8), counter-attack shots (2.4±2.4 vs. 0.5±0.6), and counter-attack goals (1.7±2.0 vs. 0.3±0.5). Between G1 and G2, six defensive variables differed: action shots (7.4±3.6 vs. 12.0±4.9), total shots (24.1±5.7 vs. 28.5±5.0), action goals (1.3±1.1 vs. 3.7±1.9), total goals (6.8±3.1 vs. 9.8±3.3), action-goal percentages (16.4%±14.3% vs. 32.1%±12.9%), and counter-attack GK saves (0.6±0.9 vs. 0.1±0.4). These results indicate that teams in the G2 group need to hone their offense abilities in counter-attack shots and action shots, and improve their ability to deter an opponent’s shots and goals, especially in counter-attack shots and action shots. Only one variable differed between G2 and G3, and that was offense action shots (14.2±4.8 vs. 9.1±3.8). It is conceivable that G2 and G3 have similar levels of performance, so further research is necessary to determine what differentiates these groups. Six offensive variables differed between G3 and G4: extra player shots (5.6±2.2 vs. 2.9±2.0), total shots (29.6±4.5 vs. 20.9±5.4), action goals (2.3±2.3 vs. 1.3±1.2), total goals (8.9±3.8 vs. 4.5±2.2), total exclusion fouls (9.0±2.8 vs. 6.5±4.3), and percentage of GK saves (29.9%±10.1% vs. 20.5%±6.7%). Six defensive variables differed between G3 and G4: counter-attack shots (0.9±1.5 vs. 2.8±2.7), center goals (1.6±1.3 vs. 3.1±2.3), action goals (3.1±2.2 vs. 5.9±3.9), total goals (10.3±4.8 vs. 17.4±5.4), action-goal percentages (22.9%±13.1% vs. 43.4%±17.4%), and total-goal percentages (33.9%±14.5% vs. 50.4%±9.0%). The differences between G3 and G4 may suggest that the games were less competitive. As Escalante et al. (2011) has noted, women’s water polo has a shorter tradition of international competition, a lower level of professionalism, and lower competitive demand. Coaches, players and others concerned with international female water polo must overcome these drawbacks in order for the World Championships to be more competitive and exciting in the future.

References


The effect of deliberate practice on the technique of national calibre swimmers

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Keywords: biomechanics, technique, instruction, measurement, drag coefficient, coaching

‘Deliberate practice’ strategies are essential to develop expert skill performance (Ericsson, Krampe & Tesch-Römer 1993). Deliberate practice components include: clear instructions, appropriate task difficulty, a sufficient number of skill repetitions, immediate feedback, individualised supervision, a variety of learning strategies, tasks designed to maintain focus in the cognitive and associative learning stages, and replication of superior performance. In contrast, traditional practice in swimming, particularly for older and more competitive teenagers, often emphasises training distance (quantity) over skill instruction (quality).

A previous study found that teenage competitive swimmers did not improve their technique (as measured by the active drag coefficient, \(C_d\)) when training with traditional practice strategies (Havriluk 2003). In another study (Marinho, Barbosa, Costa, Figueiredo, Reis, Silva & Marques 2010), an eight week training program included only ‘practicing technical drills’ (consistent with typical traditional practice) and concluded that there was no significant improvement in the \(C_d\).

In comparison, two deliberate practice studies reported impressive technique improvements. A study with young teenage swimmers showed that a one-week intervention using deliberate practice produced a significant improvement in the \(C_d\) (Havriluk 2006). In another study, swimmers practiced deliberately during a two hour intervention that included real-time video and hand force feedback and had a 22% increase in average hand force (Jefferies, Jefferies & Donohue 2012).

A general lack of emphasis on technique for (particularly more competitive) teenagers may be related to concern for interfering with success, a misperception about the potential impact on performance, and/or an emphasis on increased training distance. The purpose of the present study was to determine the effect of a deliberate practice intervention on the technique of older teenagers (national calibre swimmers) where in comparison to younger teenagers; the habit strength would likely be more resistant to change.

Method

The study participants were 19 national swim team members (11 males and 8 females) between the ages of 14 and 21. The descriptive statistics for the males were: age (\(M = 16.2\) yrs, SD = 1.4), height (\(M = 177\) cm, SD = 8.0), and mass (\(M = 65.2\) kg, SD = 8.7). The female data were: age (\(M = 17.4\) yrs, SD = 2.1), height (\(M = 168\) cm, SD = 7.6), and mass (\(M = 64.2\) kg, SD = 6.8). Informed consent was obtained.

Subjects were pretested sprinting over a 20 m swim to the wall. Hand force and swimming velocity data were collected over the last 10 m (Figure 1). The instrumentation and Aquanex testing protocol were identical to previous studies (e.g. Havriluk 2003, 2006). Each swimmer was tested for all four strokes with about 1 min rest between trials.

After the pretest, an instructional intervention included two classroom and three poolside instructional sessions. The intervention was consistent with the concepts of deliberate practice. The
specific learning strategies in the present study were designed to address the general characteristics of deliberate practice, as shown in Table 1.

![Figure 1](image.png)

**Figure 1** Captured screen from testing procedure shows synchronised underwater video image and hand force curves. The vertical gray lines are synchronised with the video image.

<table>
<thead>
<tr>
<th>General characteristic of deliberate practice</th>
<th>Specific characteristic of deliberate practice for swimming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Instructions</td>
<td>Images of model to demonstrate optimal technique</td>
</tr>
<tr>
<td></td>
<td>Precise wording of specific visual and kinesthetic cues that complement the model</td>
</tr>
<tr>
<td>Appropriate task difficulty</td>
<td>Swims with focus on the most appropriate cues</td>
</tr>
<tr>
<td></td>
<td>Drills that isolate focus on select cues</td>
</tr>
<tr>
<td>Sufficient number of skill repetitions</td>
<td>Numerous short-distance swims at a slow stroke rate with limited breathing and constant focus</td>
</tr>
<tr>
<td>Immediate feedback</td>
<td>Group and individual feedback about compliance with cues immediately after swims</td>
</tr>
<tr>
<td>Individualised supervision</td>
<td>Reminders before swims</td>
</tr>
<tr>
<td></td>
<td>Reinforcement after swims about compliance with cues</td>
</tr>
<tr>
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<td>Feedback after swims about non-compliance with cues</td>
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<td>Variety of learning strategies</td>
<td>Classroom and poolside instruction and analysis</td>
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<td>Swims and drills that isolate focus on select cues</td>
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<td>Analysis with quantitative force data and synchronised underwater video</td>
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<td>Maintain focus in cognitive and associative learning stages</td>
<td>Reminders before swims to focus on cues on every stroke</td>
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<td>Questions about focus on cues following swims</td>
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<td>Dialog between instructor and swimmers about the use of cues and attention to learning strategies</td>
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<td>Replication of superior performance</td>
<td>Emphasis on continual control of movements to replicate optimal technique</td>
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For example, a biomechanical model (Figure 2) was used as one strategy to make the technique instructions as clear as possible. Specific visual and kinesthetic cues were precisely worded to complement the model. As there was some variation in the ability level of the participants, the skills were individually modified to target the appropriate task difficulty.
Skill repetitions were limited to short distance swims at a slow stroke rate with minimal breathing to maximise focus on the cues. The intervention of this study was too short to include a sufficient number of repetitions for skill mastery; the intent was to include a sufficient number of repetitions so that the participants understood how to focus on the cues on their own while training during the month between the pretest and the posttest.

The swimmers were provided with individualised supervision in terms of reminders about cues before swims and feedback about cues immediately after swims. The inclusion of instruction and analysis in both classroom and pool environments ensured a variety of learning strategies. (Feedback about synchronised underwater video and hand force data as shown in Figure 1 is an example.) The continual emphasis on cues was designed to maintain focus in the cognitive and associative phases, as well as reinforce the necessity to replicate superior performance (optimal technique).

![Figure 2: Biomechanical model for instructing swimmers in the use of specific cues to monitor their own technique](image)

**Results**

An ANOVA found that there was a significant overall decrease (improvement) in the $C_d$ ($F = 5.9$, $p<.05$) from the pretest to the posttest (Figure 3). There was no significant change in swimming velocity (ns), but there was a significant decrease in average hand force ($F = 23.9$, $p<.05$). As shown in Figure 4, post hoc tests found a significant improvement in the effect size (ES) of the $C_d$ for both butterfly and breaststroke ($p<.05$).
Figure 3  Changes in swimming velocity, active drag coefficient, and average hand force from pretest to posttest

Figure 4  Technique improvement from pretest to posttest

Because of the minimal improvement in freestyle and lack of improvement in backstroke, the sample was stratified into specialists and non-specialists for each stroke, as classified by their coach. Specialists in butterfly, backstroke, and breaststroke were found to improve more in their specialty strokes than non-specialists.

**Discussion**

The results demonstrate that even a relatively short duration of deliberate practice can make a meaningful improvement in technique for swimmers of a very high ability level. As shown in Figure 6, the magnitude of the improvement of the older teenagers (age 16) is comparable to the data for younger teenagers (age 13) in another study using deliberate practice (Havriluk 2006). The results suggest that deliberate practice can help overcome the habit strength of swimmers who have performed millions of stroke cycles, as well as provide evidence for continued emphasis on technique instruction with older, high ability level competitors.
The results of the short-term deliberate practice treatments compare favorably to data from much longer periods of traditional practice. The deliberately practicing younger teenagers (age 13) improved their $C_d$ across all four strokes an average ES of .55σ in one week, while the difference in two years of traditional practice (between swimmers in the 11 & 12 and 13 & 14 age groups from Havriluk 2003) was only slightly larger (ES = .68σ). The deliberately practicing older teenagers (age 16) improved their $C_d$ an average ES of .30σ in one month, while the difference in two years of traditional practice (between swimmers in the 13 & 14 and 15 & 16 age groups) showed a deterioration in technique (ES = -.15σ), which can probably be attributed to an emphasis on practice quantity over quality.

Quantity of practice (training distance) is important to improve both conditioning and technique. A ‘sufficient number of repetitions’ is a necessary characteristic of deliberate practice. However, it is critical that each repetition ‘replicate superior performance’. As training distance fatigues a swimmer, repetitions are less likely to replicate optimal technique. Gauging an adequate, but not excessive, number of training repetitions is a challenging aspect of coaching. Hopefully, the findings of the present study will encourage coaches to carefully monitor swimmers to ensure that they perform a minimal number of non-optimal repetitions.

The greatest technique improvements in the present study were in butterfly and breaststroke. Rushall (2013) explained that even the world’s fastest swimmers have excess vertical motion in the bilateral strokes. The drills for butterfly and breaststroke that were used in this study were designed in part, to minimise vertical motion. It seems that activities directed at minimising vertical motion in the bilateral strokes can have a significant and immediate impact on technique for even high ability level swimmers. The greater improvement for stroke specialists than non-specialists suggests that the ‘perceived relevance of the information’ may be another deliberate practice characteristic.

The characteristics listed in Table 1 increase the opportunity for swimmers to practice deliberately. Often, logistics limit inclusion of all the strategies. For example, lack of access to a classroom, constraints on pool space, and staff limitations make it difficult to ensure a complete treatment. However, under many circumstances a number of the strategies can be successfully employed.

In particular, individual feedback about both compliance and non-compliance with specific cues is essential. If a swimmer is exposed to a cue enough times, he/she can memorise the phrase and then evaluate his/her technique while swimming. Not only does the swimmer then become proficient at monitoring his/her own stroke, but the constant self-evaluation process maintains focus in the cognitive and associative learning stages so he/she can internalise the feedback process.
Figure 6  Improvement in the active drag coefficient for younger teenagers (age 13) and national caliber swimmers (age 16) from short-term deliberate practice treatments, as compared to the two-year difference between comparable age groups.

**Conclusions**

The results demonstrate that even a relatively short duration of deliberate practice can make a meaningful improvement in technique for swimmers of a very high ability level. Because of the technique improvement, the swimmers were able to swim as fast on the posttest with less force, and therefore, less effort. It is recommended that coaches emphasise deliberate practice in all training sessions and include the specific strategies for swimming listed in Table 1. The magnitude of the effect of the deliberate practice in the present study will hopefully encourage coaches to emphasise technique instruction for even national caliber swimmers.

**References**


Relationship between heart rate variability and performance during taper and competition in elite swimmers

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Keywords: heart rate variability, autonomic nervous system, training load, performance

The aims of this study were to assess changes in heart rate variability (HRV) during a 3-week intensive training period, followed by 3 weeks of taper and one week of competition, and correlate changes in HRV with changes in performance (ΔP). In thirteen elite swimmers (6 female, 7 male) Their mean age, body weight and height at inclusion in the study was 18.3 ± 1.2 years, 55 ± 3 kg, and 167 ± 5 cm for females and 19.2 ± 1.7 years, 74 ± 2 kg and 181 ± 5 cm for males. All subjects had a history of more than 5 years of practice at national and international level. Diurnal standard indices of HRV were assessed by time domain and spectral analysis at the end of each period in supine (SU), supine control breathing (CB) and standing position (ST), and compared to a control age- and sex-matched sedentary group. The weekly training volume performed in dry-land workout (DL) and for swimming, under and above the individual anaerobic threshold (respectively LI and HI) was recorded. During the taper the swimming training load decreased substantially as well as the parasympathetic indices in standing position SD1ST (28.7 ± 18.8 vs. 18.8 ± 14.3 ms); RMSSDST (40.6 ± 41.3 vs. 26.5 ± 20.2 ms); HFST, (1141.9 ± 2733.6 vs. 400.7 ± 608.8 ms²) (P<0.05). Conversely, during the competition period, several HRV indices increased pNN50SU, (0.19 ± 0.08 vs. 0.22 ± 0.09%); RMSSDSU, (68.4 ± 32.7 vs. 82.2 ± 35.9 ms); LF SU, (2301.7 ± 1699.5 vs. 2491 ± 1690 ms²); SD1CB, (55.7 ± 22.7 vs. 70.1 ± 38.1 ms); RMSSDCB, (78.4 ± 31.9 vs. 98.3 ± 53.3 ms); HF CB, (3694.2 ± 2482.5 vs. 5342.9 ± 4403.4 ms²); (P<0.05). Improvement in ΔP was positively correlated with an increase in HF CB and a decrease in LF CB expressed in normalised units (r²=0.64, r²=-0.64, P<0.05). The decrease in low intensity training during the competition was correlated to the increase in LF/HF CB (r² = 0.64, P<0.05). Heart rate variability decreased during taper and increased during competition. During the competition week, low intensity training was associated with a higher maintenance of parasympathetic modulation.

Introduction

In high-level athletes, an optimal training load periodisation permits the achievement of peak performance during major events of the competitive season (Mujika and Padilla 2003). In this way, two to four weeks of intensive training followed by one to three weeks of reduction in training load, known as taper, has been proposed to be an effective way to improve performance (Mujika and Padilla 2003). Several studies have demonstrated that reduction of training volume decreased prior accumulated fatigue while maintaining training intensity had a fundamental role in preserving the physiological adaptations obtained during earlier overload training periods (Mujika and Padilla 2003).

Analysis of heart rate variability (HRV) is widely used in endurance sports as a practical and reliable marker of fatigue and adaptation to intensive training (Aubert et al. 2003; Yamamoto et al. 2000; Macor et al. 1996; Pichot et al. 2000; Hedelin et al. 2000) and also as an appropriate tool for monitoring training loads (Kiviniemi et al. 2007). Several studies have emphasised the changes in sympathetic-parasympathetic balance of the autonomic nervous system during different intensive training periods as well as during the periods of reduced training (Atlaoui et al. 2007; Pichot et al. 2002; Iellamo et al. 2002). In elite athletes, most research has observed that regular intensive training enhances vagal activity and tends to decrease sympathetic cardiac modulation. Conversely, during severe training bouts (James et al. 2002; Furlan et al. 1993), intensive training periods (Baumert et al. 2006) and strenuous competitive events, these effects are reversed (Bernardi et al. 1997; Cornolo et al. 2005). The cardiovascular autonomic modulation decreased and was shifted from parasympathetic
toward sympathetic predominance. Such vagal inhibition associated with a concomitantly sympathetic activity enhancement, was interpreted as a neurovegetative adaptation for increasing athletic performance (Iellamo et al. 2002). Indeed, some studies showed that an appropriate recovery period following an intensive one leads to a rebound of the global heart rate variability (Pichot et al. 2002) associated with an increase of the performances exceeding the level previously achieved (Iellamo et al. 2002). However, if the training stimulus is insufficient during taper, a decline in cardiovascular function and cardiovascular autonomic regulation can occur (Mujika and Padilla 2003).

In recent years, the number of competitions has been increased during the competitive seasons. These periods of competition periods of one to two weeks could lead to strenuous fatigue due to an accumulation of multiple stress factors (rehearsal of the competitive races, travel, jet lag, perturbations in routine). Although several studies have pointed to autonomic balance changes following an intensive single bout of exercise (James et al. 2001; Furlan et al. 1993) or a unique competitive trial (Bernardi et al. 1997; Cornolo et al. 2005), this is the first research to examine these changes over one competition week following a taper period. Thus the aim of this research was to assess the heart rate variability changes during seven weeks of training comprising an intensive 3-week training period followed by 3-weeks of taper and one week of competition. The second aim was to link the HRV changes to the performance evolution.

**Methods**

**Subjects.** Six female and seven male elite swimmers were followed for the seven weeks leading up to the national championships. Their mean age, body weight and height at inclusion in the study was 18.3 ± 1.2 years, 55 ± 3 kg, and 167 ± 5 cm for females and 19.2 ± 1.7 years, 74 ± 2 kg and 181 ± 5 cm for males. All subjects had a history of more than 5 years of practice at national and international level.

**Studied periods and performance data.** The final seven weeks of training preceding the national championships, situated in May, were studied. These seven weeks were divided into three distinct periods: the intensive training period (ITP), the taper period (TP), both 3 weeks in length (weeks 1, 2, 3 and weeks 4, 5, 6 respectively) and the competition period (CP) covering the last week (week 7). (Figure 1)

The performance change (P) between the end of ITP and the end of TP was calculated as the difference between the performance succeeding ITP (P1), recorded during preparatory events, and the performance succeeding TP (P2), recorded during the national championships. A positive performance change value indicated a performance improvement (i.e. performance was faster after TP than after ITP). Performances and performance changes were expressed as a percentage of the world record in order to scale values.

Intensity levels for swim workouts were determined as proposed by Mujika and co-researchers (Mujika et al. 1995) and detailed in Avalos et al. (2003). An incremental test to exhaustion was performed at the beginning of the season (repeated and adjusted four times) to determine the relationship between blood lactate concentration and swimming speed. Each subject swam 6 x 200-m at progressively higher percentages of their best personal competition time over this distance, until exhaustion. Blood lactate concentration was measured in blood samples collected from the fingertip during 1-min recovery periods separating each 200-m swim. Thereafter, all swimming sessions were divided into five intensity levels according to the individual results obtained during this test. These levels were defined as: level 1/ swimming speeds below ~ 2 mmol.l⁻¹; level 2/ at ~ 4 mmol.l⁻¹; level 3/ just above ~ 6 mmol.l⁻¹; level 4/ at ~10 mmol.l⁻¹ the onset of blood lactate accumulation; and level 5/ maximal swimming work. Workout in the water was quantified in meters per week covered in each intensity level. Strength training and all other physical activities prescribed by coaches outside the water were quantified in minutes per week (15, 16).
The whole of the training performed by each swimmer was synthesised in four distinct types of load. The low-intensity training load (LI) was the mean of the training volumes of the 1st to 3rd intensity levels. The high-intensity training load (HI) was the mean of the training volumes of the 4th and 5th intensity levels and included the distance swam in competition. The dry-land workouts (DL) consisted of strength training and all other physical activities included in the training program but not performed in water. The total weekly training load (TTL), representing the total physiological stress produced by the different work-out sessions, was the mean of the weekly stimulus for each training intensity. To scale intensity values, the weekly training volume of each intensity level was expressed as a percentage of the maximal weekly volume measured at the same intensity level throughout the seven weeks of the study for each subject (see 1, 15, 16 for a similar method).

HRV analysis. Each test lasted 15 minutes: 8 min in supine position (SU), 2 min in supine position with control breathing (CB), and then 5 min in standing position (ST). Recordings made at 2 to 7 min, 8 to 10 min and 11 to 14 min were retained for analysis. The RR interval (time between two successive R-waves of the recorded cardiac electric activity) was measured with a Polar S810 HR monitor (Polar®, Kempele, Finland), which has been validated in comparison with ECG recordings (Kingsley et al. 2005). Each RR interval was validated before analysis.

Related to the time domain analysis, the following indices were calculated: the mean normal RR interval (RR), the standard deviation of intervals (SD), the proportion derived by dividing NN50 by the total number of NN intervals (pNN50), and the root mean square of standard deviation (RMSSD). These measurements of short-term variations estimate high frequency variations in heart rate (Task Force of the European Society of Cardiology and North American Society of Pacing and Electrophysiology 1996). We have checked that different durations of recording did not affect HRV indices, especially SD which can be linked with to the length of the recording period (Task Force of the European Society of Cardiology and North American Society of Pacing and Electrophysiology 1996).Uusitalo et al. (1996) demonstrated that the stronger the parasympathetic activity, the greater were SD and RMSSD in athletes.

Fast Fourier Transform (FFT) was applied to calculate the spectral power using Nevrokard HRV software (Nevrokard®, Medistar, Ljubljana, Slovenia), with tachogram frequency-responsive re-sampling (RR interval vs. time) in order to obtain equidistant points (2 Hz re-sampling). The Hanning windowing function was applied and the Goertz algorithm was used for calculation. Window width was 30 data points. The algorithms of the variability analysis of the differences between the R-waves look for sinusoidal similarities in the signal. This analysis provides the cumulated spectral power of a particular frequency, corresponding to the number of events of the given sinusoidal function. The spectral power was measured by frequency bands in ms.Hz according to the recommendations of the Task Force of the European Society of Cardiology and North American Society of Pacing and Electrophysiology (1996). The following indexes of heart period variability were computed: total power (Ptot), spectral power in the low-frequency (LF; 0.04-0.15 Hz) and high-frequency (HF; 0.15-0.40 Hz) bands expressed in absolute values (ms²) as well as in normalised units (nu) which represent the relative value of each power component in proportion to the total power minus the very low frequency component (VLF; ≤ 0.04 Hz). HF is in large part composed of efferent vagal activity (Uusitalo et al. 1996). The LF component is considered by some investigators to be in particular a marker of sympathetic activity especially when it is expressed in normalised units. Consequently, the LF/HF ratio can be considered to mirror sympathovagal balance (Task Force of the European Society of Cardiology and North American Society of Pacing and Electrophysiology 1996).

Statistical analysis. To assess evolution of training load and HRV indices between ITP, TP and CP, the variables were compared using Freidman ANOVA. Coefficients of determination were calculated to highlight the relation between training loads, HRV indices and performance change. For all analyses, the level of significance was set at P<0.05. All calculations were made with Statistica 6.0 software (StatSoft Inc, Tulsa, OK, USA).
Results

Training loads and heart rate variability evolution between the different periods. LI and HI decreased from ITP to TP (P<0.05), DL also decreased. From TP to CP, DL and BI decreased (P<0.05) whereas HI increased slightly. Concerning the evolution in HRV between ITP and TP, there was a noticeable decrease in the majority of time domains and spectral HRV indices which were significant in the standing position for SDNNST, RMSSDST, and HFST (Table 2). From TP to CP, control breathing values of SDNNCB, RMSSDCB, and HFCB indices as well as standing values of the pNN50ST, RMSSDST, and LFST indices increased (P<0.05) (Tables 1 and 2).

Longitudinal relationships between HRV indices, training and performance. Performance increase was linked to control breathing HFnu increase (r² = 0.64, P<0.05) and to control breathing LFnu and LF/HF decrease (r² = 0.64, r² = 0.69 respectively, P<0.05) (Figure 2). The decrease in BI training during CP was correlated to the increase in control breathing LF/HF ratio (r² = 0.64, P<0.05, Figure 3). Conversely, sympathetic indices in supine position (LFSU) were positively linked to TTL and DL during the competition period (r² = 0.53, r² = 0.50 respectively, P<0.05) (Figure 4). So, TTL, DL and LFSU changed in the same way.

Discussion

During the taper period the total training load, low and high intensity training decreased (-61%, -71%, -40% respectively), and a significant decline in the indices of the parasympathetic modulation was observed in the standing position (SDNNST, -34%; RMSSDST, -35%; HFST, -65%), suggesting that the autonomic adaptations acquired during intensive training reversed. Some studies analyzing the diurnal heart rate variability throughout short-term reduce training periods following over-load periods indicate close results (Atlaoui et al. 2007; Gamelin et al. 2007). Atlaoui and his collaborators (2007) studying 13 elite swimmers, failed to show any diurnal HRV indices changes between an intensified training period and a 3-week taper period. Along the same lines, Gamelin and co-workers (2007) observed in ten healthy young men who completed 12 weeks of aerobic training a moderate HRV decreased from the 2nd week of recovery. In this latter research, sympathetic activity decreased more rapidly than the parasympathetic suggesting that detraining could involve an abrupt decrease in the autonomic control accompanied by a slow shift toward a parasympathetic predominance until both branches return to pre-training values (Gamelin et al. 2007).

Assessing nocturnal HRV activity during the two-week period of reduce training succeeding a period of intensified training, Pichot et al. (2000) in middle distance runners and Garet et al. (2004) in five of seven regional swimmers have reported a maximal rebound rising above the level achieved at the end of the training period in the overall autonomic activity with a significant shift in the autonomic nervous control toward a predominance of its parasympathetic branches. Contradictory findings among studies are probably the result of different research designs (Aubert et al. 2003; Atlaoui et al. 2007). Independent variables such as age, gender, standards of performance, training state, the nature of the sport practiced, as well as the precise duration and distribution of training loads, which are known to influence the HRV responses, were not precisely checked among studies (Aubert et al. 2003; Sandercock et al. 2005; Atlaoui et al. 2007).

Swimmers who maintained the most parasympathetic control and lowered the sympathetic influence were characterised by significantly higher performance improvements between the preparatory competition and the national championships. These results could confirm those obtained during previous cross sectional (Joyner et al. 1992; Smith et al. 1989) and longitudinal studies (Atlaoui et al. 2007; Garet et al. 2004; Pichot et al. 2002; Schmitt et al. 2006). It has been shown in swimmers that both the initial HF level (Atlaoui et al. 2007), as well as the significant increase in HFnu and decrease in LFnu (Garet et al. 2004) are associated with an increase in performance during taper. In eight national-level male swimmers, Schmitt et al. (2006) observed that the decrease in parasympathetic activity induced by 17 days of intensive training correlated with a lower 2000-m freestyle.
performance. Accordingly, Pichot et al. (2000) found a shift toward parasympathetic dominance after a week of recovery following 3 weeks of intensified training load in middle distance runners.

In the present study, however, the statistical significance between the improvement in performance and the variations of the autonomic activity during taper depended heavily on the values monitored on one outlier subject (subject 2). When this subject was removed from the overall population the statistical relations between HF, LF and performance changed ($r^2=0.64$ and $r^2=0.64$; $P<0.05$ respectively with subject 2 and $r^2=0.45$; $r^2=0.45$; $P=0.12$ without subject 2). This subject presented characteristic symptoms of a short-term sympathetic overreaching syndrome (Fry et al. 1991; Hedelin et al. 2000). He performed worse during the national championship after taper and reported a clear shift of the autonomic balance toward a sympathetic dominance which had been associated with a maintenance in the total score of fatigue. This subject stopped training during the sixth and the seventh weeks preceding competition due to illness (flu and pharyngitis). In order to compensate for the preceding lack of training, he did not decreased his training load during taper as much as the overall population (e.g., the total training load, strength training, high and low intensity swimming training decreased from intensive to the taper period by 27.8%, 58.3%, 21.2%, 22.1% respectively).

During the competition week the indices of both the parasympathetic and sympathetic activity increased according to an equivalent proportion. These results are in contrast with preceding research reporting a decrease in all the autonomic indices associated with a shift of the sympathovagal balance toward a dominant sympathetic modulation as much as 72-h hours following long and intensive exercise (Baumert et al. 2006; Bernardi et al. 1998; Hautala et al. 2001; Cornolo et al. 2005; James et al. 2002; Dixon et al. 1992; Furlan et al. 1993). In eight trained athlete runners, a training bout consisting of six consecutive 800-m performed just under $v$VO$_2$ max led to persistent decrease in all the heart rate variability indices up to 72h after the exercise session (James et al. 2002). Competitive trials performed in altitude induced similar responses: an increase in resting HR happened during the early recovery period and after both an increase in sympathetic modulation and a decrease in parasympathetic activity (Bernardi et al. 1998; Cornolo et al. 2005). Similar results were recorded in another study in which Hautala et al. (2001) observed, after 1 day of recovery following a 75-km cross-country ski race, strengthened responses consisting of an increased resting HR and sympathetic modulation associated with a decreased parasympathetic activity. To our knowledge, only the study of Hedelin et al. (2000) did not demonstrate any changes in diurnal HRV in which nine elite canoeists completed a 6-days training camp (13 ± 6 h) consisting of cross-country skiing and strength training corresponding to a 50% increase of the current training load.

The relationships between HRV activity and training load evolution between taper and competition was in agreement with previous research in which different HRV responses were reported depending on the type and the intensity of training (Aubert et al. 1998, 2001, 2003; Verlinde et al. 2001). In the present study, swimmers who decreased the least LI training between taper and competition exhibited a lower LF/HF ratio which indicates a predominance of parasympathetic over sympathetic drive. Moreover, the greater was the decrease in the total and dry-land training load during the competition week, the lower was the sympathetic control increase in supine position. This agrees with the findings of previous research which higher parasympathetic activity was observed in athletes who followed an aerobic training program compared with those who participated in anaerobic training sessions. (Aubert et al. 2001, 2003; Verlinde et al. 2001; Iellamo et al. 2002). Similarly, Iellamo and his colleagues (2002) have emphasised that moderate intensity training (i.e., 75% of maximal training load) induces an increase in parasympathetic control associated with a decrease in resting heart rate whereas training more intensively (i.e., 100% of the maximal training load) leads to an increase in sympathetic regulation and resting heart rate with a decrease in parasympathetic regulation.

**Conclusion**

In conclusion, HRV analysis appears to be a promising non-invasive method for monitoring the decrease in training loads during taper and for evaluating the stress induced by a prolonged
competition period. During taper, this method may be helpful in evaluating the optimal training load decrease and in regulating the high-intensity, low-intensity and strength training proportions. Indeed, during taper, insufficient training load and too low aerobic training could induce a decrease in parasympathetic regulation. Conversely, overload strength and intensity training could shift the cardiac autonomic balance toward a predominance of sympathetic over parasympathetic drive.

References


Assessing the evolution of swim training via a review of Doc Counsilman’s training logs

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Keywords: coaching, swimming, training and history

Introduction

Athletes, coaches, and sport scientists endeavor to maximise sport performance through optimal, preplanned training regimes. In the history of competitive swimming, Dr James ‘Doc’ Counsilman is considered legendary and credited with introducing innovative and pioneering training methods. He strove to produce a more effective training paradigm for elite competitive swimmers, which emphasised the specificity of training for each athlete. Under Counsilman’s leadership and guidance, Indiana University’s men’s swim team won six consecutive National Collegiate Athletic Association (NCAA) championship titles (1968 to 1973) and 23 Big Ten conference titles (including 20 consecutive team championships from 1961 to 1980). Forty-eight of Counsilman’s Indiana swimmers competed in the Olympic Games, representing ten nations, and winning 46 medals (including 26 gold). His most celebrated pupil was Mark Spitz, who won seven gold medals in the 1972 Olympics, all in world-record time, and consequently, he was accredited for coaching the most dominant Olympic swimming campaign by any country after the USA men’s swim performances at the 1976 Games.

At his retirement, Counsilman indicated that he was most proud of his many contributions to the science of swimming as his swimmers were ultimately responsible for their own swim successes. Counsilman is credited with proposing that Bernoulli’s Principle is relevant to propulsive forces generated during competitive swim strokes. He is also reported as having introduced interval training and dry land exercise as the central training paradigm for swimming. Furthermore, Counsilman introduced essential equipment used in current competitive training programs such as pace clocks and pool-lane markers.’ He is the first swim coach who meticulously documented many of these training methods in his book ‘The Science of Swimming’, published in 1968. It has since become a
fundamental textbook and virtual ‘swimming bible’ for swim coaches worldwide and been translated, to date, into more than 20 languages.

Perhaps most importantly in the present context, while coaching at Indiana University, Dr Counsilman and his assistants recorded their daily workouts 1) in order to have a history of each swimmer’s progress and 2) as a means of differentiating techniques that were successful from those that were not. However, there has never been any systematic analysis of how his training trends and actual coaching practices ‘evolved’ during Counsilman’s thirty-year tenure at Indiana University. Given the influence of Counsilman’s training practices on swim training in the broadest sense, a careful review of these logs may prove to be of historical interest. The purpose of this study was to track the application of Counsilman’s training methods over his last two decades at Indiana University by initiating a quantitative analysis of his team’s short-course fall and winter training logs.

**Methods**

Training logs from three college swim seasons (September-March) recorded by Dr Counsilman and his assistants were examined: 1968-69, 1977-78 and 1987-88 seasons. Because of the fact that different people recorded the workouts in each of the three years chosen, variations existed in how similar data were recorded. The swimmers participating in Counsilman’s workouts were different as well. Pre-season practices took place in a 50-meter outdoor facility for a variable length of time. In the late fall, practices moved indoors to a 22.85-meter (25-yard) competitive facility (Royer Pool) on the Indiana University campus. A season was defined as being 25 weeks in length, starting backwards from the NCAA championship held in March (25th week). Each season was divided into four training phases; pre-season, preparatory, intense training, and tapering phases following Counsilman (1968). The analysis was centered on the last week of each training phase. Data points for the analysis were taken from the 1st, 8th, 16th and 24th weeks.

Physical training for competitive sport is described as being a combination of training frequency, distance, and intensity (Wenger and Bell 1986). For this study, training frequency and distance were calculated from the number of weekly sessions and swimming distance, respectively, for the 1st, 8th, 16th, and 24th weeks of each season. Training intensity was estimated based on Counsilman’s description, and the demand of each swim training set was estimated by classifying it into one of five intensity categories by following Maglischo (2003):

1. **Warm-up and recovery (W&R):** Sets at the beginning and end of a training session were classified into this category (Stress Index: 1).
2. **Base:** Swimming speed in this category is lower than the speed for the lactate threshold. (Stress Index: 2)
3. **Threshold and above (TA):** Swimming speed is higher than the speed for the lactate threshold. The length of a set is more than 457 meters with less than a one minute rest interval (Stress Index: 6).
4. **Lactate tolerance (LCT):** Swimming speed is close to race speed (Stress Index: 8).
5. **Lactate production (LCP):** Maximal effort spring swimming. Set length is not more than 457 meters (Stress Index: 4).

The physiological stress score of each set was calculated as the product of swimming distance (meter) and the stress index (Maglischo 2003; Mujika 1995; Sharp 1993). The weekly stress score was computed as the mean of stress score for the sessions each week as follows:

\[
\text{Weekly stress score} = \frac{\text{total weekly WBA (meter) \times 1 + Base (meter) \times 2 + TA (meter) \times 6 + LCT (meter) \times 8 + LCP (meter) \times 4}}{\text{number of sessions per week}}
\]
In addition, the mean proportion of kick, pull, and swim training sets per session in each week was calculated.

**Results and discussion**

**1968-69 season**

*Frequency*: The training frequency increased from three training sessions per week during the 1st week to five times per week in the 8th week. Five afternoon sessions per week were maintained in the 16th week. In the 24th week, the sessions increased to seven practices per week.

*Distance*: The mean training distance (± SD) per session was 3626 ± 437 meters in the 1st week. The distance increased to 5173 ± 461 meters in the 8th week and decreased to 4561 ± 401 meters in the 16th week. In the 24th week, it was the fewest, 2177 ± 636 meters. Total weekly training distance increased from approximately 11,000 meters in week 1, to 26,000 meters in week 8 and 16 and back to approximately 15,000 meters in week 24.

*Intensity*: In the 1st week, 55% of total distance was covered with Base. In the 8th week, the emphasis of training intensity shifted to TA, accounting for 63% of the total distance. In the 16th week, the percentage of training in the LCT range was the highest among the four weeks, indicating an intense training phase. The stress score increased progressively from the 1st week through the 16th week, (12,667, 24,620, and 26,640 in the 1st, 8th, and 16th, respectively) and decreased to 7,507 at week 24.

**1977-78 season**

*Frequency*: There were six (five afternoons and one morning) training sessions in the 1st week of this season. Thirteen training sessions were offered in the 8th and the 16th weeks, although only 9 were required (11 for distance swimmers). Practice sessions were offered six mornings a week, and five afternoon sessions weekly. A third daily practice session was offered twice weekly in the early evening specifically designed for sprint training and referred to as ‘sprinters delight’. The sessions offered decreased to ten times per week in the 24th week.

*Distance*: The mean training distances per session were 4174 ± 1432, 5558 ± 1417, 4841 ± 1451, and 1570 ± 337 meters in the 1st, 8th, 16th, and 24th week, respectively. Total weekly training distance increased from approximately 25,000 meters in week 1 to 72,000 meters in week 8; 62,000 meters in week 16 and then back to approximately 20,000 meters per week in week 24.

*Intensity*: Emphasis on TA was evident in the 1st, 8th, and 16th weeks. LCT was employed throughout the season. The highest stress score was observed in the 8th week. The stress score increased from the 1st week to the 8th week (19,533 to 28,146) and decreased in the 16th and 24th weeks (23,892 and 2,740, respectively).

**1987-88 season**

*Frequency*: In the 1st week of the season, there were 6 training sessions, one per day (five afternoons sessions and one Saturday morning). Nine training sessions were recorded in the 8th and 16th weeks of the season (four mornings and five afternoons). In the 24th week, there were 8 practices.

*Distance*: A similar mean training distance per session was observed in the first three phases of the season (4083± 677, 4182 ± 817, and 4357 ± 534 meters, respectively), but training distance decreased to nearly half (2482 ± 418 meters) in the 24th week. Total weekly training distance for sprint and stroke groups increased from approximately 25,000 meters in week 1, to 39,000 meters in weeks 8 and 16, and to approximately 20,000 meters in week 24.

*Intensity*: About two third of the total distance was in the TA range for the 1st and 8th week (75 and 60%, respectively). This season started with a higher stress score (22,416), while the stress scores
were similar between the 8th (19,461) and 16th (19,411) weeks but decreased to 6787 in the 24th week.

**Comparison among three seasons**

**Frequency (Table 1)**

During the phases of preparatory (week 8) and intense training (week 16), the number of weekly training sessions increased from five in 1968-69 to thirteen in 1977-78, and decreased to nine in 1987-88 (Table 1). In the 1977-78 season, 13 sessions were available but distance swimmers were required to attend minimum of 11 sessions, and nine sessions for other swimmers. The least number of training sessions was observed in the 1st weeks (pre-season phase) in all seasons.

<table>
<thead>
<tr>
<th>Week</th>
<th>1968-69</th>
<th>1977-78</th>
<th>1987-88</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>3</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>8th</td>
<td>5</td>
<td>13 (9-11)</td>
<td>9</td>
</tr>
<tr>
<td>16th</td>
<td>5</td>
<td>13 (9-11)</td>
<td>9</td>
</tr>
<tr>
<td>24th</td>
<td>7</td>
<td>10*</td>
<td>8</td>
</tr>
</tbody>
</table>

*Five out of ten training sessions consisted of self-planned trainings with the designated distance.

In 1977-78, distance swimmers were required to attend 11 sessions and nine sessions were required for other swimmers.

**Distance (Figure 1)**

The training distance varied among the 1st, 8th, 16th and 24th weeks in all seasons. The total swimming distance per session (sprint and stroke groups) during the 1st and 16th weeks (pre-season and intense training phases) was similar among all three seasons, although there was a quite difference in the distance per session during week 8th (preparatory phase) between the 1st two seasons and the 1987-88 season. Total training distance per week in 1977-78 in sprint and stroke groups represented 130%, 94% and 92% increases over weeks 1, 8 and 16 in 1968-69 respectively. Training distance during week 24 in 1977-78 was similar to in 1968-69. In 1987-88, total weekly distance remained approximately the same as in 1977-78 during week 1, decreased in weeks 8 and 16 by 25% and 10%, respectively, and increased by approximately 26% in week 24.
**Intensity (Table 2 & Figure 2)**

Emphasising TA in the 8th and 16th weeks was consistent across two decades. In the 16th week of all seasons, the training of LT was employed relatively more as compared to the other weeks. Mean stress score per week was similar during the 8th and 16th and between 1968-69 and 1977-78 seasons, but decreased in the 1987-88 season. During the 24th week (tapering phase), stress scores were similar for all three seasons.

**Table 2  Percent emphasis of intensity**

<table>
<thead>
<tr>
<th>Week</th>
<th>1968-69</th>
<th>1977-78</th>
<th>1987-88</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W&amp;R Base TA LCT LCP</td>
<td>W&amp;R Base TA LCT LCP</td>
<td>W&amp;R Base TA LCT LCP</td>
</tr>
<tr>
<td>1st</td>
<td>12 55  33 0 0</td>
<td>20 14 65 0 1</td>
<td>12 10  75 3 0</td>
</tr>
<tr>
<td>8th</td>
<td>11 16 70 0 3</td>
<td>17 13 66 1 3</td>
<td>24 11 60 2 3</td>
</tr>
<tr>
<td>16th</td>
<td>13 10 51 24 2</td>
<td>13 20 62 4 1</td>
<td>18 28 35 15 4</td>
</tr>
<tr>
<td>24th</td>
<td>39 21 27 5 8</td>
<td>33 42 19 0 6</td>
<td>42 19 31 2 6</td>
</tr>
</tbody>
</table>

The intensity the training of 'on the house' during 24th week in 1977-78 was undetermined.

W&R: warm-up and recovery, TA: threshold and above, LCT: Lactate tolerance, and LCP: lactate production.

**Figure 2  Mean weekly stress scores for the three seasons analyzed**

**Proportion of kick, pull, and swim training sets**

Mean proportion of kick, pull, and swim training per week for the three seasons are shown in Table 3. Swim training accounted for more than 50% of a session in all weeks in the three seasons. The ratio of kick and pull training were constant throughout a season and between seasons.

**Table 3  Proportion of kick, pull, and swim training in the three seasons**

<table>
<thead>
<tr>
<th>Week</th>
<th>1968-69</th>
<th>1977-78</th>
<th>1987-88</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Swim Kick Pull</td>
<td>Swim Kick Pull</td>
<td>Swim Kick Pull</td>
</tr>
<tr>
<td>1st</td>
<td>70 18 12</td>
<td>74 12 14</td>
<td>76 12 12</td>
</tr>
<tr>
<td>8th</td>
<td>72 14 14</td>
<td>72 14 14</td>
<td>59 18 23</td>
</tr>
<tr>
<td>16th</td>
<td>75 11 14</td>
<td>68 15 17</td>
<td>70 13 17</td>
</tr>
<tr>
<td>24th</td>
<td>64 19 17</td>
<td>65 18 17</td>
<td>56 22 22</td>
</tr>
</tbody>
</table>
**Summary**

The present study analyzed Counsilman’s training logs and analyzed the characteristics and the obvious ‘evolutionary trends’ within his swim training plan. Because the important comparisons here are being made with essentially three seasons (1968-69, 1977-78 and 1987-88), only limited statistical approaches are of any value in the present context. Nevertheless, within each of the competitive seasons reviewed, Counsilman’s general swim training plan (on a semi-annual basis) was consistent across two decades. Training during the pre-season and preparatory phases focused upon aerobic base training and later in the season shifted towards anaerobic base training. This transition in focus is supported by the recent literature (Maglisicho 2003; Bampa 1999). Training distance also transitioned during the swim season as did training stress levels. Analysis of training frequency was complicated by the fact that Counsilman commonly provided three supervised practice sessions per day for the swimmers to attend (only two mandated). During the winter season of 1977-78 twice a week he offered a fourth training session (three mandated) specifically for sprinters—though nearly all his swimmers attended. The first session was scheduled early morning (6 am) with the next sessions beginning at 1:30 and then again at 3:30 pm. Swimmers could attend either afternoon session depending upon conflicts with their class schedules. A final practice session, designed specifically for sprint training, began at 7 pm in the evening.

As is true for every team, it is possible that the variation in Counsilman’s training was, in part, influenced by the ability level of the swimmers on the team at the time of analyzed seasons. For example, in the 1968-69 season, Indiana won the NCAA championship title with 15 swimmers. In the 1977-78 season, however, the team placed 7th with 14 swimmers. We do not believe, however, that the training trends observed were masked by, or are reflective of, the competitiveness of the swimmers to any real extent. Rather, they were specifically designed by Counsilman *a priori* and reflect the changes in training theory and practice that transpired during this era.

With our analysis, we concluded that Counsilman’s training methods shifted from fewer, but more intense training sessions in the 60s, to more frequent practices and much greater training distances in the 70s. Finally, by the late 1980s coaches were moving towards a more moderate approach, with much greater focus on specialised training directed towards each athlete’s specific competitive event. As Counsilman frequently stated, his belief was that coaches should ‘treat athletes as equals but train them as individuals’. The trends in his training logs appear to reflect this gradual shift in thinking.

**References**


**Biophysics of the elite endurance swimmer: a case study during aerobic capacity evaluation using different methods**

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**Keywords:** oxygen uptake, biomechanical parameters, aerobic capacity evaluation, swimming training

**Abstract**

Introduction: In swimming research, the characterisation of various parameters are generally accomplished by its reduction to the mean and standard deviation. This procedure allows analyzing the tendencies and/or the variability of a group. However, in doing so, individual characteristics of an elite swimmer may be hidden by the group tendency. Thereby, the purpose of this case study was to analyze one elite endurance swimmer comparing biomechanical and physiological parameters among the main methods used for aerobic capacity evaluation.

Methods: The elite female endurance swimmer (18 yrs, 1.64 m, 56 kg, 91.3% 400m freestyle WR) performed in different days: 1) an intermittent incremental protocol until voluntary exhaustion to determine the velocity (v) associated at the individual lactate threshold (ILT), the ventilatory threshold (VT), the heart rate threshold (HRT), the lactate threshold of fixed 3.5mmol.L⁻¹ (LT3.5), maximal oxygen uptake (VO₂max), and minimal v that elicits VO₂max (vVO₂max); 2) three 30min sub-maximal continuous tests to determine the v and oxygen uptake (VO₂) kinetics associated at the maximal lactate steady state test (100%MLSS), above (102.5%MLSS) and below (97.5%MLSS) this intensity. Blood lactate collection (BLa), v, ventilatory, energetic and biomechanical parameters were controlled in all tests.

Results: The results showed a close relationship among the 100%MLSS, ILT and VT regarding the v, ventilatory, energetic and biomechanical parameters. Meanwhile, LT3.5 and vVO₂max presented higher values in all these parameters. Key points were noticed: 1) the oxygen uptake efficiency values (OUE) presented an uncommon stability and linear relationship with the v until VO₂max while the remaining swimmers showed decreased values of OUE, largely determined by metabolic acidosis and pulmonary dead space (Sun, Hansen & Stringer 2012). Thus, this maintenance of OUE may be explained by the low BLa observed in swimmer’s vVO₂max (4.4mmol.L⁻¹); 2) VO₂ slow component was not observed in both intensities of 100%MLSS and 102.5%MLSS; 3) the 100%MLSS v was very high (92.6% vVO₂max) implying low VO₂ values (77.5% VO₂max).

Conclusion: Thereby, the analysis of individual characteristics of specific athletes, particularly elite swimmers, rather than relying upon mean sample values, may be decisive to understand the specific intervention required and to improve performance.

Acknowledgments: This research was supported by grants from the Capes Foundation, Ministry of Education of Brazil (BEX: 0536/10-5), and Projeto PTDC/DES/101224/2008 (FCOMP-01-0124-FEDER-009577).

**Introduction**

In sports science, the characterisation of the transversal or longitudinal behaviour of most performance relevant parameters, such as the maximal oxygen uptake (VO₂max), has been generally accomplished by its reduction to the mean and standard deviation analysis. This allows one to study the tendencies and/or the variability of a group. However, in doing so, the individual characteristics of an outlier swimmer may be hidden by the group tendency: and this swimmer may be extremely relevant; as a record holder, for instance.
On the other hand, when an elite athlete that show expressive results at national and international levels is analyzed as a case study, it might be possible to highlight biophysical specificities that may inform his hone training process, as well as the pathway to be followed by lower performance level swimmers. Thereby, the purpose of this case study was to analyze an elite endurance swimmer comparing biomechanical and physiological parameters among the most-known methods used for the aerobic capacity evaluation, emphasising the particular adaptations that may help the achievement of best results.

**Methods**

One elite female endurance swimmer (18 yrs, 1.64 m, 56 kg and 12% body fat mass) volunteered to participate in the present study, signing a form of informed consent before participation. At the time experiments, the personal best 400 m freestyle swim was 91.2% of the 25 m pool world record. The test sessions were performed in a 25 m indoor swimming pools within a five days period, and at the same time of the day (± 2 h) to minimise the effect of circadian rhythm variation on the test (Atkinson & Reilly 1996). The swimmer warmed up at moderate aerobic intensity at 1000 m swim, and was advised to refrain from intense training sessions at least 24 h before the experimental sessions. Tests were performed in front crawl, using in-water starts, and open turns without underwater gliding.

Initially, the swimmer performed a front crawl intermittent incremental v protocol until voluntary exhaustion, with repeated (~7)x distances of 200 m, increments of 0.05 m.s\(^{-1}\) and 30 s rest intervals between each step. The predetermined v of the last step was defined by the best time at the 400 m front crawl race and to define all the v steps (Fernandes et al. 2006). The intermittent incremental protocol was realised to determine the v output provided by the main methods used for the aerobic capacity and power – VO\(_{2}\)max—evaluation. All the correspondent values of gas exchange, energetic and biomechanical parameters were also determined. Interpolation procedures were used for this purpose, based on a polynomial regression model and calculated between the incremental velocities and the correspondent relevant parameters (Neter, Wasserman & Kutner 1985).

The ILT was assessed through the mathematical curve fitting method between lactate and v values (Machado et al. 2006). The LT3.5 was determined by the fixed 3.5 mmol.L\(^{-1}\) value of Bla and its correspondent v (Heck, Mader & Hess 1985). The VT was determined using the v slope method and its respective values of pulmonary ventilation (V\(_E\)), defining a disproportional increase of V\(_E\) concerning the increase of locomotion speed during the incremental test (Svedahl & MacIntosh 2003). The HRT was determined by the curve slope method calculated between v and heart rate (Cellini et al. 1986), assuming that the curve inflection point corresponds to the HRTv.

Subsequently, the swimmer performed three 30 min submaximal constant swimming tests at imposed paces for determination of the v associated to the maximal lactate steady state (100%MLSS). The first trial was performed at the ILTv, and a negative delta in Bla was observed (97.5%MLSS). Further, two subsequent trials with 2.5% higher velocities were performed to find the 100%MLSSv and above the 100%MLSSv (102.5%MLSS), in which at the 102.5%MLSS (Pelarigo, Denadai & Greco 2011), the swimmer was not able to maintain the v and attained exhaustion at 27th min of test. The 100%MLSSv was defined as the highest intensity in which the Bla did not increase more than 1 mmol.L\(^{-1}\) between the 10th and 30th minute of swim (Heck, et al. 1985). The MLSS test is considered the gold-standard direct method for the aerobic capacity evaluation.

Earlobe capillary blood samples were collected: 1) at rest, at the end of each intermediate step of the incremental test during the 30 s interval, and immediately after and at each 2 min of recovery the last step, until the Bla recovery peak was found; 2) at rest, at the 10th and 30th min (or voluntary exhaustion) of each continuous swimming test to assess Bla. Capillary Bla was assessed through a portable lactate analyzer (Lactate Pro, Arkray, Inc.). All the blood samples collection lasted around 30s.
Gas exchange were measured by a telemetric portable gas analyzer (K4 b², Cosmed, Italy) attached to a newest respiratory snorkel and valve system (New AquaTrainer, Cosmed, Italy), with a low hydrodynamic resistance (Baldari et al. 2012), that was connected to the swimmer in all the tests. The oximeter was calibrated before each test. The heart rate (HR) was monitored and registered continuously by a heart rate monitor system (Polar Vantage NV, Polar electro Oy, Kempele, Finland) and real-time transferred through a telemetric signal to the portable oximeter.

The control of swimming v was obtained using a visual underwater pacer on the bottom of the pool (GBK-Pacer, GBK Eletronics, Aveiro, Portugal) with lights located each 2.5 m. The swimmer’s head should be above each visual signal. Exhaustion was assumed and the test ended when the swimmer remained 5 m behind the light.

In all each tests, the VO₂ data were analyzed and the occurring errant breaths caused by coughing, swallowing, and sighing were excluded from the local mean. Afterwards, the gas exchange values were characterised as ± 3SD, and the values outside this amplitude were removed. To all swimmer’s data, the breath-by-breath data were subsequently averaged to provide 5 s mean values. In the incremental test, the gas exchange parameters values obtained in the last minute of each step were retained and the mean value considered to be the representative of that step. The continuous test was split into seven time moments corresponding to the 4th min, 25%, 33%, 50%, 66%, 75%, and 100% of the total test duration. Again, the 1 min period before each time moment was retained to calculate the mean values of that moment in the time duration of the test. The VO₂max was considered to be reached in accordance to conventional physiological criteria (Howley, Bassett Jr & Welch 1995).

The energetic parameters were described by the total energy expenditure (Ė) and the energy cost (C). In the 100%MLSS, those parameters were calculated at the 10th and 30th min, the same time moments used for Bla, and in the incremental test they were calculated at the final 1 min of each step of exercise. The Ė values were obtained through the addition of the aerobic and the anaerobic energy expenditure. The aerobic energy expenditure was considered to be expressed by the difference between the exercise oxygen uptake (VO₂exercise) and the baseline oxygen uptake (VO₂baseline) (mL.kg⁻¹.min⁻¹); the anaerobic energy expenditure was obtained by the Bla net values transformed into O₂ equivalents through the constant multiplicative value of 2.7 mL.O₂.kg⁻¹.MM⁻¹ (Barbosa et al. 2008). C was determined as the ratio of Ė and its respective v (di Prampero 1986).

The VO₂ kinetics was described as a single-exponential (equation 1 and 2) or bi-exponential (equation 3) function of time by the following equation:

\[
\begin{align*}
VO_2(t) &= VO_2_{baseline} + A_1 \left[ 1 - e^{\frac{-t}{\tau_1}} \right] \quad (1) \text{ (cardiodynamic component)} \\
VO_2(t) &= VO_{2baseline} + A_p \left[ 1 - e^{\frac{-t-TD_1}{\tau_p}} \right] \quad (2) \text{ (primary component)} \\
VO_2(t) &= VO_{2baseline} + A_p \left[ 1 - e^{\frac{-t-TD_2}{\tau_p}} \right] + A_s \left[ 1 - e^{\frac{-t-TD_3}{\tau_s}} \right] \quad (3) \text{ (slow component)}
\end{align*}
\]

Where VO₂(t) represents the absolute VO₂ at the considered time moment, VO₂baseline is the resting VO₂, A₁ and τ₁ are the amplitude and the time constant of the cardiodynamic component; A₁, TD₁, and τ₁ are the amplitude, the time delay and the time constant of primary component, respectively; A₂, TD₂, and τ₂ are the amplitude, the time delay and the time constant of slow component, respectively. The cardiodynamic component terminated at the start of primary component (TD₁), the primary component terminated at the start of slow component (TD₂). The VO₂ kinetics was calculated at the first 10 min and the last 20 min (or exhaustion time) of exercise.

The biomechanical parameters were assessed through a dry land video camera operating at a frequency of 50 Hz, allowing to analyse two stroke cycles in the middle of the swimming pool. The stroke rate (SR) was determined by the number of cycles per unit of time (cycles.min⁻¹), the stroke length (SL) by the ratio of v (m.min⁻¹) and SR, and the stroke index (SI) was the product of v (m.s⁻¹) and SL. These parameters were analysed in each 50 m of each step of incremental test, and averaged for
the entire step. At the 100%MLSS, the biomechanical parameters were obtained at each one of the seven time moments corresponding to the 4th min, 25, 33, 50, 66, 75, and 100% of the total test duration, during the last 1 min of each time moment. The mean value of each parameter at all time moments was assumed as representative of the test.

**Results**

The results showed a narrow relationship among the 100%MLSS, ILT and VT methods, with similar values of \( v \), gas exchange and energetic parameters. However, the biomechanical parameters showed to be different when 100%MLSS was compared to the all other pace assessment methods under evaluation. The LT3.5 overestimated most of the variables compared to the 100%MLSS and the other methods, providing closest values to the characteristic of \( VO_2 \) \(_{\text{max}}\). The indirect HRT test underestimated the most of the variables which were characterised in the 100%MLSS. The 100%MLSS corresponded to high percent values of the \( v \) correspondent to maximal oxygen uptake (\%\( VO_2 \) \(_{\text{max}}\)). However, the respective \( VO_2 \) values did not attain high percent of maximal oxygen uptake (\%\( VO_2 \) \(_{\text{max}}\)) compared to intensity values (Table 1).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Global swim analysis evolving ( v ), gas exchange, energetic and biomechanical parameters compared to the most-known methods for the aerobic capacity evaluation in an elite female endurance swimmer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100%MLSS</td>
</tr>
<tr>
<td>( v ) (m.s(^{-1}))</td>
<td>1.33</td>
</tr>
<tr>
<td>%( VO_2 ) (_{\text{max}}) (%)</td>
<td>93%</td>
</tr>
<tr>
<td>Bla (mmol.L(^{-1}))</td>
<td>1.8</td>
</tr>
<tr>
<td>( VO_2 ) (mL.kg(^{-1}).min(^{-1}))</td>
<td>53</td>
</tr>
<tr>
<td>%( VO_2 ) (_{\text{max}}) (%)</td>
<td>78%</td>
</tr>
<tr>
<td>( V_\text{CO2} ) (L.min(^{-1}))</td>
<td>2.61</td>
</tr>
<tr>
<td>( \dot{V}_E ) (L.min(^{-1}))</td>
<td>73.4</td>
</tr>
<tr>
<td>R</td>
<td>0.89</td>
</tr>
<tr>
<td>HR (beats.min(^{-1}))</td>
<td>193</td>
</tr>
<tr>
<td>%HR ( VO_2 ) (_{\text{max}}) (%)</td>
<td>95%</td>
</tr>
<tr>
<td>( \dot{E} ) (mL.kg(^{-1}).min(^{-1}))</td>
<td>46.2</td>
</tr>
<tr>
<td>C (kJ.m(^{-1}))</td>
<td>0.68</td>
</tr>
<tr>
<td>SR (cycles.min(^{-1}))</td>
<td>34.6</td>
</tr>
<tr>
<td>SL (m_cycle(^{-1}))</td>
<td>3.21</td>
</tr>
<tr>
<td>SI</td>
<td>3.09</td>
</tr>
<tr>
<td>time/100m (min)</td>
<td>1’14”96</td>
</tr>
</tbody>
</table>

\( VO_2 \) kinetics at 97.5%, 100% and 102.5% MLSS are presented in Table 2. \( VO_2 \) kinetics values were obtained during the first 10 min (10 min) of exercise, and during the last 20 min of exercise (20 min) or voluntary exhaustion. There was a tendency to increase the \( VO_2 \) with the increase of intensity. The swimmer did not present slow component in any intensity.
Table 2  

<table>
<thead>
<tr>
<th></th>
<th>97.5%MLSS</th>
<th>100%MLSS</th>
<th>102.5%MLSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO₂_{baseline} (mL.kg.min⁻¹)</td>
<td>7.0</td>
<td>12.4</td>
<td>5.2</td>
</tr>
<tr>
<td>Aₚ (mL.kg.min⁻¹)</td>
<td>43.2</td>
<td>36.5</td>
<td>48.8</td>
</tr>
<tr>
<td>TDₚ (s)</td>
<td>9.9</td>
<td>8.1</td>
<td>28.4</td>
</tr>
<tr>
<td>τₚ (s)</td>
<td>14.9</td>
<td>15.2</td>
<td>7.9</td>
</tr>
</tbody>
</table>

Regarding the oxygen uptake efficiency values (OUE) (Figure 1), the swimmer showed a relatively wobbling profile during the incremental test, but with a tendency to keep constant values. It is interesting to note the sudden increase of OUE at the 6th step, which was coincident with the intensity of the ILT, followed by a persistent tendency to reduced values (Left Panel). When the behaviour of OUE values around the 100%MLSS was analyzed, the swimmer presented decreased values at the 102.5%MLSS after 33% of test duration, whereas at the other intensities tested, the OUE values maintained stable throughout time (Right Panel).

![Figure 1](image)

**Figure 1**  The OUE values throughout an incremental test until voluntary exhaustion in the case study swimmer (Left Panel); and the OUE values at 97.5%, 100% and 102.5% MLSS in the case study swimmer (Right Panel).

**Discussion**

The purpose of this study was to investigate the most well-known and used methods for the aerobic capacity evaluation, comparing among them the gas exchange, energetic and biomechanical parameters in an elite female endurance swimmer.

The swimmer showed specific physiological adaptations normally presented by endurance athletes, such as the MLSS intensity at a high %\(\text{VO}_{2\text{max}}\) (93%) compared to a relative lower oxygen uptake—%\(\text{VO}_{2\text{max}}\) (78%), supporting the observed high OUE at this particular intensity. Accordingly, low values of BLa at MLSS and \(\text{vVO}_{2\text{max}}\) (1.8 and 4.4 mmol·L⁻¹, respectively) were observed, reinforcing the high adaptation to the prevalence of aerobic metabolism sustaining exertion. This phenomena is usually reported in the literature in which these kind of athletes exhibit a lactate to velocity curve shifted to the right (Holfelder, Brown & Bubeck 2013), allowing them to keep high velocities in a physiological steady-state at intensities near the \(\text{vVO}_{2\text{max}}\). Indeed, such endurance athletes present higher phenotypic expression of oxidative muscle fibers compared to sprint athletes (Tanaka & Swensen 1998), and fibers which consumes lactate (Gladden 2008), allowing to support the total energy expenditure required in high swimming intensities, explaining the typical low final BLa values observed in swimmers like the one analyzed in this study.
In the present study, the investigated swimmer presented a VO\textsubscript{2max} of 68 mL.kg\textsuperscript{−1}.min\textsuperscript{−1}, slightly higher than the 65 mL.kg\textsuperscript{−1}.min\textsuperscript{−1} found as representative of female endurance swimmers (Rodriguez & Mader 2011). Commonly, endurance specialists are characterised by a very high VO\textsubscript{2max} values, determining a predominance of the aerobic energy pathways, and an elevated capacity to sustain metabolic balance intensities. Moreover, in this type of athletes, such the swimmer in study, VO\textsubscript{2} correspondent to 100%MLSS reaches values close to maximal, and a steady-state occur at a higher level of muscle and lactate concentrations (Rodriguez & Mader 2011).

The swimming economy, described in this paper as energy cost (C), is defined by the ratio of the total energy expenditure (\textepsilon) and v. It have been considered as the major determinant of swimming performance (di Prampero, Pendergast & Zamparo 2011). In this study, the investigated swimmer presented C and \textepsilon values at MLSS, expressed as percentages of VO\textsubscript{2max} of 81% and 74.2%, respectively. When the C value of the preferable intensity to train aerobic capacity is compared among different assessment methods, the higher values were observed for the 100%MLSS. This was so once 100%MLSS was also the method that prescribed higher v values compared to the LT, VT and HRT methods (C = 7.4, 5.9 and 2.9%, respectively). This suggests that the exercise mode (continuous or intermittent) may contribute differently to the adjustments of swimming efficiency, with continuous exercise showing to be more economical. The C (0.68 and 0.84 kl.m\textsuperscript{−1}) and \textepsilon (46.2 and 62.3 mL.kg\textsuperscript{−1}.min\textsuperscript{−1}) values at 100%MLSS and VO\textsubscript{2max} respectively, corroborating the literature concerning the similar sub-maximal intensities (Zamparo et al. 2005) and the maximal aerobic power intensities (Chatard, Lavoie & Lacour 1991).

Regarding the biomechanical parameters, the swimmer demonstrated different adjustments between the 100%MLSS and other methods. In the 100%MLSS test, the SR was higher and the SL was lower compared to LT, VT and HRT methods, and the SR was lower and SL was similar compared to the LT3.5 method. These biomechanical adjustments seem to follow the differences observed in C and \textepsilon between the exercise mode (continuous and intermittent), in which the increased intensity of intermittent exercise has been attributed to factors such as lactate removal and restoration of creatine phosphate (Billat 2001). These aspects may influence differences in technical adjustments occurred between continuous and intermittent exercise. Furthermore, as the continuous exercise is affected by the muscular fatigue established throughout exercise duration (Sahlin, Katz & Broberg 1990), athletes tend to adopt the most economical mechanical adjustments to keep a given intensity (Baron et al. 2005; Zamparo et al. 2001).

Usually, researches define the 100%MLSS as the upper boundary of heavy and/or lower boundary of severe intensity domains (Burnley & Jones 2007; Xu & Rhodes 1999). At or above this 100%MLSS intensity, the VO\textsubscript{2} slow component is assumed to be evident (Burnley & Jones 2007). However, in this case study, the swimmer did not shown any VO\textsubscript{2} slow component, either at 100%MLSS or above this intensity, explained in part by the low Bla. Indeed, endurance athletes present high percentage of oxidative muscle fibers, lactate consumers, as previously described, not requiring additional and progressive anaerobic contributions to the energy expenditure, one of the determining factors to develop VO\textsubscript{2} slow component (Cannon et al. 2011).

One of the more interesting issues raised about this swimmer and its specific physiological adaptations is perceived through OUE values, indicator of ventilatory efficiency (Sun, Hansen, Garatachea, Storer & Wasserman 2002). The case study swimmer presented a stable and almost linear OUE values variation with increasing velocity until exhaustion, while the mean tendency of national level swimmers decreased the OUE values, due to factors as the metabolic acidosis and pulmonary dead space (Baba et al. 1996). It is important to underline that the case study did not showed high values of Bla to keep high velocities near the v VO\textsubscript{2max} in a physiological steady-state. Moreover, the OUE showed similar values in all the three continuous intensities around the 100%MLSS until 33% (± 10 min) of all tests, do not been affected by both metabolic acidosis and physiologic pulmonary dead space, status indicators of the systemic and pulmonary perfusion (Baba...
et al. 1996). However, just after 33% of the total time duration, the unbalance exercise (102.5%MLSS) clearly showed the decrease of ventilatory efficiency (OUE), leading to exhaustion.

Thereby, the analysis of individual characteristics of specific athletes, particularly elite swimmers, rather than rely upon mean sample values, may be decisive to understand the specific individual characteristics and required intervention, and to improve performance.

Acknowledgments
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References


Can swimmers with Down syndrome follow a visual pacer in an incremental protocol?

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Keywords: Down syndrome, visual feedback, pacing, eligibility test

Introduction

Down syndrome is one of the most common genetic causes of intellectual disability (1). This condition occurs when there is an extra copy of the 21st chromosome. This gene over-expression leads to a highly complex and variable phenotype, in which physical and cognitive development are significantly altered (2). In total, there are over 80 clinical features occurring more frequently among individuals with Down syndrome than the population at large (3).

Despite this, there is a very pronounced lack of knowledge on factors leading to sport success in these individuals, particularly in swimming. The well known positive relationship between physical activity and health may be even more important for individuals with disabilities. For these individuals physical activity can help them to improve ability to perform daily life activities, a critical factor in maintaining independence (4, 5, 6). Nevertheless, few investigations report findings in trained individuals with intellectual disabilities (7), even more in the case of a specific disability, such as Down syndrome. Furthermore, too often, one is left with the belief that the nature of the intellectual disability renders it impossible for a person to engage in the level of training or mental preparation required for high level competition (7).

The ability to follow a race strategy might be a potential problem for persons with an intellectual disability. This is important to optimal performance. Little is known about this ability. In a previous study on race analysis for swimmers with Down syndrome (8), it was observed that for the 100 m
freestyle these swimmers presented significant differences in speed and stroke rate from the 1st to the 2nd laps, and from the 2nd to the 3rd laps. Especially for stroke rate, there was a marked decrease on the 2nd lap, and a little less decrease on the 3rd lap. This could mean that swimmers with Down syndrome have trouble on pacing well in the race. The aim of this study was to verify if swimmers with DS are able to follow a visual pacer, and maintain velocity when swimming without the pacer.

Method

Eight male swimmers with Down syndrome, all participants at the 2nd European Swimming Championships for Down syndrome, in Portugal, took part in the study. All swimmers trained approximately 8 hours a week. They performed a 4x100 m front crawl incremental protocol at 75%, 80%, 85%, and 90% of best time for a 100 m race. Each 100 m was divided in 2x50 m with a 10 sec rest. After each 100 m, swimmers rested for 1 min. The first 50 m were conducted with a visual pacer (Pacer 2 Swim, by KulzerTEC), and the second 50 m without. In this case, the swimmer was asked to maintain the speed of the first 50 m. All swimmers performed 3x50 m at the 1st pace speed with the lights on, to become familiar with the device. Differences (paired t-tests) between target and real times were calculated with and without pacer lights as well as between real time with and without lights (SPSS 17.0) for all intensities. Correlations were also analyzed. Significance was set at p < 0.05.

Results

Mean target time ranged from 58.4s ± 5.9 (75%) to 48.7s ± 3.9 (90%) (Table 1). At all swimming intensities, significant correlations were found between 50 m with the pacer and the target time (0.82 for 75%, 0.92 for 80%, 0.90 for 85%, and 0.98 for 90%) (Table 2). There was a significant difference between target time and time without pacer only at 75% pace (-5.0s ± 6.6). In the other cases there was no systematic difference. Nevertheless the 95% CL of the differences were >5s from the mean at 75% and 80% and >3s from the mean at higher intensity. Interestingly without pacing lights swimmers performed slower than target at lower intensity and above target at higher intensity (1.7s ± 4.27: 90%).

Table 1  Mean and standard deviation (SD) for the 50 m with and without pacer at 75%, 80%, 85%, and 90% of best time, and target time for each intensity

<table>
<thead>
<tr>
<th></th>
<th>Mean (s)</th>
<th>SD</th>
<th>Target Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75% with pacer</td>
<td>54.70</td>
<td>5.95</td>
<td>58.40</td>
</tr>
<tr>
<td>75% without pacer</td>
<td>53.39</td>
<td>7.16</td>
<td>58.40</td>
</tr>
<tr>
<td>80% with pacer</td>
<td>53.54</td>
<td>5.15</td>
<td>54.73</td>
</tr>
<tr>
<td>80% without pacer</td>
<td>54.10</td>
<td>7.60</td>
<td>54.73</td>
</tr>
<tr>
<td>85% with pacer</td>
<td>49.93</td>
<td>5.30</td>
<td>51.50</td>
</tr>
<tr>
<td>85% without pacer</td>
<td>51.86</td>
<td>4.21</td>
<td>51.50</td>
</tr>
<tr>
<td>90% with pacer</td>
<td>48.08</td>
<td>4.39</td>
<td>48.65</td>
</tr>
<tr>
<td>90% without pacer</td>
<td>50.40</td>
<td>5.16</td>
<td>48.65</td>
</tr>
</tbody>
</table>
Table 2  Correlations between the target time, and times with and without pacer for all intensities

<table>
<thead>
<tr>
<th>Pair</th>
<th>Target Time</th>
<th>Correlation</th>
<th>Sig</th>
<th>Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:</td>
<td>75% &amp; with pacer 75%</td>
<td>0.82</td>
<td>0.014</td>
<td>-3.69 ± 3.45</td>
</tr>
<tr>
<td>2:</td>
<td>75% &amp; without pacer 75%</td>
<td>0.43</td>
<td>0.284</td>
<td>-5.00 ± 6.65</td>
</tr>
<tr>
<td>3:</td>
<td>80% &amp; with pacer 80%</td>
<td>0.92</td>
<td>0.001</td>
<td>-1.19 ± 2.04</td>
</tr>
<tr>
<td>4:</td>
<td>80% &amp; without pacer 80%</td>
<td>0.42</td>
<td>0.300</td>
<td>-0.63 ± 7.00</td>
</tr>
<tr>
<td>5:</td>
<td>85% &amp; with pacer 85%</td>
<td>0.90</td>
<td>0.002</td>
<td>-1.58 ± 2.38</td>
</tr>
<tr>
<td>6:</td>
<td>85% &amp; without pacer 85%</td>
<td>0.38</td>
<td>0.356</td>
<td>0.36 ± 4.68</td>
</tr>
<tr>
<td>7:</td>
<td>90% &amp; with pacer 90%</td>
<td>0.98</td>
<td>0.000</td>
<td>-0.58 ± 0.98</td>
</tr>
<tr>
<td>8:</td>
<td>90% &amp; without pacer 90%</td>
<td>0.59</td>
<td>0.126</td>
<td>1.75 ± 4.27</td>
</tr>
</tbody>
</table>

Discussion

In spite of repeated practice with pacing lights DS swimmers were initially not able to repeat the pace when feedback was removed. Nevertheless when practice was limited to one trial they were more successful. As intensity increased they moved from over estimation (too fast) to underestimation (too slow).

The visual pacer can be a very interesting instrument for swimming training. The training of cadence techniques (pacing) is well known and is often used by trainers and swimmers. The pacer provides the swimmer with visual feedback, that he recognises allowing the swimmer to evaluate himself and to monitor his performance during a training task in a simple constant and efficient way. In psychological terms it can be an excellent reinforcement for the swimmer who can concentrate much more on the task for example regulation of stroke frequency. As people with Down syndrome have an intellectual disability, there was the question if they could be able to follow a visual stimulus and furthermore retain the information acquired. The swimmers in this study had little or no practice using the lights and the system itself is not always available.

Furthermore as target speed increased swimmers changed from over to underestimation of the required swimming speed. This might be a form of overcompensation. This might indicate that the swimmers were able to use the feedback but that more practice is needed.

Besides the importance that this kind of instrument can have in swimming training, this kind of pacing training can have a good transfer to competition. As it was observed by Querido et al. (2012), swimmers with Down syndrome seem to have difficulties in pacing well in the competition. They presented significant differences in speed and stroke rate between the 1st and 2nd laps, and between 2nd and 3rd laps. If swimmers with Down syndrome are able to use the feedback given by the pacer lights, they can probably be trained and improve this kind of ability. As said before, swimmers from the present study had no practice with this kind of equipment. In the future, could be interesting for coaches to develop this kind of approach with swimmers with Down syndrome, and try to understand if their swimmers can follow a pacing training and improve in the proposed test. After this, swimmers should be evaluated at the race to understand if this kind of training can actually influence the race performance.

Conclusion

At the moment this study shows that swimmers with Down syndrome are not able to take advantage of short term visual feedback to maintain a pacing strategy. Further work is needed to see if more practice improves performance in the test itself, if this possible improvement is sustained over time and how this exactly influences race performance. Additional work is also needed under more fatiguing situations. Furthermore reference data from swimmers without intellectual disability and for all groups in other stokes is necessary. Potentially this simple test might be used in an eligibility test (classification) not only for those with Down syndrome but for persons with other intellectual disabilities.
Acknowledgment
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References

Comparison of the training load during high-intensity interval resisted training programmed by different exercise duration

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Keywords: sprint training, blood lactate, heart rate

Introduction
Training for competitive swimmers is characterised by its high volume swimming mileage, compared to other individual sport events. However, several studies investigated whether this high volume training is actually necessary for high performance achievement compared to high intensity training (Faude et al. 2008; Sperlich et al. 2010). These results suggested that high intensity (low volume) training could also enhance endurance capacity and race performance by the same amount as the traditional high volume (low intensity) training. Therefore, new training program introducing high intensity workouts is a matter of concern nowadays.

An epoch-making training procedure of High Intensity Interval Training (HIIT) had been introduced by Tabata et al. (1996), a training regimen of 20 sec exercise at 170%VO₂max intensity with 10 sec interval repeated by 8 sets, so-called ‘Tabata Protocol’. This training protocol was suggested to enhance not only maximal accumulated oxygen deficit (anaerobic capacity) but also VO₂max (aerobic capacity). Furthermore, Ogita et al. (2010) reported an even shorter training set, 5 sec supra-maximal swim with 10 sec rest repeated by 5 sets, which indicated to have a potential to increase VO₂max as well as the glycolytic system. Even with these clear evidences of the HIIT to enhance the swimmer’s...
physiological capacity, it is hard to introduce this concept to the actual training field, because these training effects have been tested in swimming flume condition.

To realise the HIIT in actual training situation we attempt to combine HIIT with a traditional Sprint Resisted Training, which is a common training method for sprint training utilising elastic rubber tube (Maglischo 2003). The purpose of this study was to investigate and compare the training load during this new High Intensity Interval Resisted Training (HIIRT) programed by different exercise duration.

**Method**

**Experimental design**
A HIIT that could be performed in normal swimming pool situation was programed by combining traditional sprint resisted training together. An elastic rubber tube was connected to the starting block and to the swimmer by a swimming belt. Each swimmer swam at maximum effort against the elastic rubber tube. Three trials were investigated consisted by 5 sec, 10 sec or 20 sec maximal effort swim with 10 sec passive rest interval repeated by 5 sets. All participants swam all trial with front crawl stroke in spite of their specific swimming style. Each trial was conducted with one week in between. Blood lactate accumulation (Bla) and heart rate (HR) were measured after each trail. Video was recorded throughout the trial and stroke frequency (SF) was investigated.

**Subjects**
Six well-trained college swimmers participated in this study (male=3, female=3). The average FINA point in their specialised style was 751 ± 93 point. One male and three female specialised in sprint event (50, 100 m) and the other two male subjects specialised in butterfly stroke and individual medley (Table 1). The subjects were made fully aware of the risks, benefits and stresses of the study and their informed consent was obtained.

**Measurement of physiological parameter**
Before the trial and 0, 3, 5 min after the trial, blood samples were obtained from the fingertip and Bla (Lactate Pro, LT-1710, Arkray, Japan) was measured. The highest Bla after the trail was defined as the peak Bla and utilised for analysis. Heart rate count for 10 sec was reported immediately after the trial by the swimmer and the reported number was multiplied by six for investigation. All subjects were accustomed to measuring HR in their daily training.

**Measurement of stroke parameter**
Over water view of each trial was filmed by a digital video camera. Time to complete three-stroke was measured during the middle of each five maximum swimming sets from the filmed movie. Three-stroke-time was converted to stroke frequency (SF, cycle/min) for further analysis.

**Statistical analysis**
All data are reported as mean ± standard deviations. One-way repeated-measures ANOVA followed by Bonferroni corrections was performed to analyze the statistical difference of peak Bla and HR data between each trial. Two-way repeated-measures ANOVA (set × trial) followed by Bonferroni corrections was performed to determine the difference in SF. The statistical significance level was set at 5% (p < 0.05).

**Results**
Peak Bla after each set was 7.3 ± 1.7, 10.2 ± 2.7 and 12.7 ± 1.7 mmol/l, respectively (Fig. 1A). Significant difference was observed between each trial (p<.05).
HR immediately after each set was 148.0 ± 4.9, 164.0 ± 8.2 and 178.0 ± 7.3 bpm, respectively (Fig. 1B). HR of 10 sec and 20 sec trial was significantly higher compared to 5 sec trial (*p < .05). The individual results of Bla and HR is shown in Table 1. Result of the change in SF during five sets in each trial is demonstrated in Fig. 2. A two-way ANOVA revealed a main effect of trial (*p < .05), suggesting higher SF throughout the set with shorter duration trial.

**Table 1** Individual results of Bla and HR after each high intensity interval resisted training trial

<table>
<thead>
<tr>
<th>Subjects</th>
<th>sex</th>
<th>speciality</th>
<th>Bla (mmol/l)</th>
<th>HR (bpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>5sec</td>
<td>10sec</td>
</tr>
<tr>
<td>A</td>
<td>male</td>
<td>Individual Medley</td>
<td>5.9</td>
<td>7.6</td>
</tr>
<tr>
<td>B</td>
<td>male</td>
<td>Butterfly</td>
<td>7.9</td>
<td>12.7</td>
</tr>
<tr>
<td>C</td>
<td>male</td>
<td>Freestyle - Sprint</td>
<td>10.3</td>
<td>13.4</td>
</tr>
<tr>
<td>D</td>
<td>female</td>
<td>Breaststroke - Sprint</td>
<td>6.1</td>
<td>6.8</td>
</tr>
<tr>
<td>E</td>
<td>female</td>
<td>Backstroke - Sprint</td>
<td>5.8</td>
<td>11.1</td>
</tr>
<tr>
<td>F</td>
<td>female</td>
<td>Backstroke - Sprint</td>
<td>7.8</td>
<td>9.3</td>
</tr>
<tr>
<td>Ave</td>
<td></td>
<td></td>
<td>7.3</td>
<td>10.2</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td></td>
<td>1.7</td>
<td>2.7</td>
</tr>
</tbody>
</table>

**Figure 1** Average peak blood lactate (A) and heart rate (B) after each high intensity interval resisted training trial, *p < .05

**Figure 2** Average stroke frequency change during five sets of each high intensity interval resisted training trial. Significant main effect of trials was detected (*p < .05)
**Discussion**

This study aimed to investigate and compare the training load during a new High Intensity Interval Resisted Training (HIIRT) programmed by different exercise duration. Understandably, longer exercise stimulus resulted in higher glycolytic and cardiovascular demand, confirming the excellence of the ‘Tabata Protocol’. However, it was clarified that the 5 sec set could also stimulate the anaerobic system sufficiently with significantly high SF.

Deminice et al. (2010) reported a Bla level of 10.9 ± 1.2 mmol/l after the eight 100 m maximum swims with 10 min interval, which is common high intensity sprint training. Our HIIRT, when conducted with 10 and 20 sec duration, shown a similar Bla concentration compared to this traditional sprint training indicating that this short HIIRT can also stimulate the glycolytic energy system by a same degree.

Furthermore, HR after 20 sec HIIRT coincided with the recommended level for VO$_2$-max intensity endurance training (Maglischo 2003; Pyne & Goldsmith 2005). These results suggested that the HIIRT, especially with 20 sec maximum exercise – 10 sec interval protocol, has a potential to enhance anaerobic and aerobic capacity similarly with the report by Tabata et al. (1996). The explainable expected mechanism of this very short training regimen to enhance aerobic capacity could be the adaptation in the skeletal muscle after this high intensity training stimulus. Terada et al. (2001) reported that high-intensity intermittent exercise training elevated both GLUT-4 content and maximal glucose transport activity in rat skeletal muscle to a level similar to that attained after low-intensity prolonged exercise training, which has been considered a tool to increase GLUT-4 content maximally. Further investigation is warranted to examine if HIIRT could achieve a training effect in swimmers resembling with the previous studies.

SF results, however, demonstrated a significant lower value at 20 sec trial compared to shorter duration protocol. In competitive swimming, not only physiological capacity but also stroke technique is an important factor to achieve high race performance. Low SF indicates a different stroke mechanics compared to the swimming stroke during competition, particularly for sprint events. Ogita et al. (2010) reported that stroke efficiency, evaluated by MAD system, improved after 5 sec maximum swimming – 10sec interval protocol conducted in a swimming flume. Therefore, it was indicated that 5 sec trial has a benefit to stimulate the glycolytic system maintaining preferable stroke technique for sprinters.

Focusing on sprinters, a high peak Bla value was observed after 5 sec trial in Subject C (10.3 mmol/l, Table 1). We could not include sufficient number of male sprinters in this study, however, in can be speculated that shorter duration HIIRT protocol can stimulate the glycolytic system more efficiently for sprinters, possibly by the lower capacity of PCr resynthesis during the 10 sec rest interval period (Tomlin & Wenger 2001). Additionally, Ogita et al. (2010) recommended repeating the 5 sec trial twice in one training session to attain significant enhancement in race performance. As significant low peak Bla and HR was observed in this study, repeating this trial may increase the training load to a beneficial level to enhance the physiological capacity.

**Conclusion**

Examining High Intensity Interval Resisted Training in this study, it was indicated that longer exercise stimulus resulted in higher glycolytic and cardiovascular demand. However, it was suggested that the 5 sec set could also stimulate the anaerobic system sufficiently with maintaining competition related stroke mechanics, especially for sprinters.

**References**


Change of critical speed in swimmers aged 10–11 years old

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Abstract

The purpose of this research was to study the effect of aerobic and anaerobic training in critical swimming speed during the second training cycle after five months of training in swimmers aged 10 to 11 years. The method of critical speed is used as an alternative method because it is simple, inexpensive and non-intrusive. Many distance combinations are used to determine critical speed of swimming. The research involved 16 active pre-pubertal swimmers. Seven of them (n = 7) were boys, age: 10.9 ± 0.9 years, and 9 of them (n = 9) were girls, age: 11.0 ± 0.7 years. Their basic technique was freestyle swimming and all of them were swimmers of short and middle distance. The mathematical model calculates the value of critical speed distances, 50m, 100m, 200m and 400m. Subjects underwent a series of tests carried out on three different periods. The results showed that there is no statistical significant difference between the two genders and the three different measurements (Sig .651 and Sig .259 respectively). In individual level, boys and girls had a statistical significant improvement in critical speed over the different measurements (Sig .000 and Sig .000 respectively). From the findings of this research it appears that critical speed obtained with mathematical determination, can be used as an alternative to determine the appropriate speed for endurance training in children and young swimmers. The results of the research can lead to the following conclusion: The critical speed varies from period to period studying individually boys and girls.

Introduction

Critical speed has occupied researchers in order to find its true meaning and the perfect way to introduce in the coaching process (Toubekis & Tokmakidis 2013). A big part of training in swimming is executed with different energetic systems maximum speed, which aims to improve endurance in swimming. It is important for the coach to know the speed limits that should used to improve the particular endurance of swimmers without possible causing unwanted burden during a training cycle. Critical speed is a valuable tool for each trainer, easy and cheap as procedure and can help to develop a detailed of different intensities used in training program. Furthermore, critical speed must change with change with training.
Various methods for measuring aerobic and anaerobic capacity of swimmers have been applied (Bonel et al. 1980) as well as for determining appropriate loads (Costill et al. 1985). In swimming distances of 15 to 100m (Thanopoulos et al. 2008), 50 to 400 meters (Wakayoshi et al. 1992) are usually used and in some cases of elite swimmers testing procedures distances from 50 to 1500 meters (Fernandes & Vilas-Boas 1999; Dekelerle et al. 1999). Many combinations are used to determine the critical speed of swimmers (Martin & Whyte 2000). The duration of used distance must different at least 5 minutes while for the calculation 2 to 4 attempts are required (Hill 1993; Bosquet et al. 2002). Choosing one of these, coaches can check the changes in the ability of their swimmers as a result of the adjustments of their body adaptation in the process of training (Smith et al. 2002).

A research of Wakayoshi et al. (1992; 1992a) was to create a simple test which could assess the endurance capacity of swimmers. This method includes swimming at maximum intensity, with the determination of the linear regression equation between different distance and the time required to cover it. The calculation of critical velocity become the subject of many investigations (Dekerle et al. 1999; Dekerle et al. 2002) both for its low cost and secondly because it is a reliable indicator of aerobic capacity.

Investigations in swimming have shown that the activation of energy systems in efforts of maximum intensity differs from children compared to adult swimmers (Takahashi, Bone, Spry, Trappe & Troup 1992) because children exhibit different oxygen consumption (Fawkner & Armstrong 2003). In swimming athletes start maximum intensity trainings from quite an early age (Denadai et al. 2000). Also, children and young swimmers have not stable characteristics of their technique compared to adult swimmers. It is therefore necessary to study the critical speed in children under this restriction.

The aim of this research was to study the effect of aerobic and anaerobic training in critical speed during the second training cycle after five months of training in swimmers aged 10 to 11 years old.

**Methods**

**Sample**

The research involved 16 active pre-pubertal swimmers. Seven of them (n = 7) were male: age—10.9 ± 0.9 years; body height—151 ± 7 cm and weight—36.40 ± 7.4 kg and nine (n = 9) were girls, age—11.0 ± 0.7 years, with body height—152 ± 7 cm and weight—42.0 ± 9.0 kg. Their basic technique was freestyle swimming and all of them were swimmers of short and middle distance. All of them had competitive experience for at least two years. The study was approved by the ethical committee of the University.

**Procedures**

All swimmers participated in two hours daily training at least five days a week. Training involved during the first period 90% aerobic and 10% anaerobic training and they were completing 3 km. During the second period, the training was 3.5 km with 80% aerobic and 20% anaerobic and third period they were swimming 2.5 km with 75% aerobic and 25% anaerobic training. In anaerobic training the pace was similar to competition with 50m sprints and split distances before competition.

Swimmers were informed about the purpose of the research and the measurement procedures and they gave with their parents their written consent. Afterwards we proceeded with the conduction of measurements. All participants executed a warm up of 800 meters with the guidance of their coach.

From all athletes we measured body height and body weight in the afternoon between 17:00 to 19:00 before training in the gym. Considering that critical speed is calculated reliably from distances that can be completed over a period of 2-10 minutes, distances were adjusted so as to cover this range of time. The measurements were completed randomly in 4 different sessions. Swimmers were instructed to swim with maximum intensity freestyle swimming.
Critical velocity was calculated from performance time in the distances of 50m, 100m, 200m and 400m swimming (Wakayoshi et al. 1993) executed with maximum intensity and time required to cover each swimming distance (Figure 1). In order to complete the procedures, swimmers swam the above distances in three different periods. The first measurement was performed on the second phase of basic preparation period of the summer cycle, the second measurement on preparation season and the third on pre-competition period. The third measurement was performed 10 to 15 days before the main competition. Each measurement was carried out in three sessions. The athletes swam with the maximum speed the distances of 50m and 100m on the first session. On the second session they swam 200m and on the last session 400m. Each distance was measured starting from the water, taking into account swimming regulations and always with the same conditions. All measurements were performed in an open swimming pool of 50 meters with a water temperature of 26°C ± 1°C. Their aim was to improve aerobic capacity and achieving the best performance during the national championships in July. The performance of each distance was recorded with electronic watch Seiko Water Resistant 10Bar S140.

**Method of mathematical determination of critical speed**

The mathematical model calculates the value of critical speed of the distances 50m, 100m, 200m and 400m. The calculation of critical speed (V_{crit}) includes the following: the time required for the swimmer to swim the distances (50m, 100m, 200m, 400m) on a linear function of the link distance—time (Figure 1) (MacLaren & Coulson 1999; Martin & Whyte 2000; Dopsaj et al. 2000; Thanopoulos et al. 2008). The constant a is the value of y for x = 0 and is called the equation stable, while the constant b determines the slope of the line and is called regression coefficient.

![Figure 1](image.png)

Note: The slope of the line expresses the critical swimming velocity (example of one swimmer).

**Statistics**

The results were first submitted to a descriptive analysis to calculate basic statistical parameters (means, standard deviations). Also for the identification of the difference between genders we used the two way analysis of variance ANOVA. For the individual study of girls and boys we used one way analysis ANOVA for repeated measurements.

<table>
<thead>
<tr>
<th></th>
<th>CV (50,100,200,400)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>January</td>
</tr>
<tr>
<td></td>
<td>MIN</td>
</tr>
<tr>
<td>Boys</td>
<td>0,9067</td>
</tr>
<tr>
<td>Girls</td>
<td>0,9290</td>
</tr>
</tbody>
</table>
Table 2. Anova Results

<table>
<thead>
<tr>
<th>CV</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two way Anova</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>.207</td>
<td>.651</td>
</tr>
<tr>
<td>Phases (monthly measurements)</td>
<td>1.395</td>
<td>.259</td>
</tr>
<tr>
<td>One way Anovas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boys</td>
<td>25.817</td>
<td>.000*</td>
</tr>
<tr>
<td>Girls</td>
<td>43.647</td>
<td>.000*</td>
</tr>
</tbody>
</table>

*Statistical significance between different measurements for separately boys and girls p<0.05

Results

We measured 16 swimmers in the distances of 50, 100, 200 and 400 meters. The averages and standard deviations of the critical speed for boys and girls in each different measurement are presented in Table 1.

The analysis of variance showed that there were no statistically significant differences between the three measurements on the critical speed for the whole sample (Sig. .259).

Also, there were no statistically significant differences in the critical speed between the two genders (Sig. .651).

Studying the sample to an individual level, significant difference was found between the measurements of critical speed of girls (Sig .000) and boys (Sig .000), which showed that the critical speed improved from the first to the last measurement.

Conclusion

This investigation examined the effect of training after five months on critical speed of swimmers aged 10-11 years.

The aerobic and anaerobic swimming training positively affected the performance of these swimmers. The performance improvement in the distances of 50m, 100m, 200m, and 400m. was able to alter the value of their critical speed. The results of this research support the view that in early stages of training periods, a slight and steady increase in the value of critical speed is observed while there is also important improvement in later stages of training (Peak Performance Subscribe 2005).

In conclusion, five months of training for swimmers aged 10-11 years, had a positive effect on the critical speed as tested in this sample of boys and girls separately.

The critical speed could be studied in a larger sample of swimmers. It is proposed to carry out investigations with larger sample of swimmers to draw clearer conclusions on these results. Also, further studies are worth examining combinations of distances to calculate the critical speed and other age groups of swimmers regardless of their level of performance.

From the findings of this research it appears that the critical speed can be used as an alternative tool for the determination of the appropriate speed for endurance training in children but does not differ in relation to gender.

References


The evaluation of efficiency of individual programs for altitude training of elite swimmers upon metabolic and biomechanical criteria

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1 Northern (Arctic) Federal University, Russia, 2 Russian Swimming Federation, 3 Swedish Swimming Federation

Keywords: altitude training, metabolic and mechanical power and efficiency, individual training programs

Introduction

Current technology for preparing elite swimmers suggests simultaneous development of dominant energy systems and efficient biomechanical patterns (swimming technique). In the case of non-stationary movements of a swimmer in the water medium, at the 1st stage metabolic energy with some loss is transferred into mechanical energy, then at the 2nd stage with additional loss mechanical energy is transformed into useful result – swimming velocity.

The metabolic energy necessary to perform muscular work is submitted by both aerobic and anaerobic energy delivering systems [1, 2]. Fig. 1 illustrates the relative contributions of oxidative \( E_{ai(o.s.)} \), phosphogenic \( E_{ai(f.s.)} \) and lactacid \( E_{ai(l.s.)} \) energy systems to the overall active energy metabolism \( E_{ai} \) in athletes in relation to the duration of the performed work. The figure clearly shows a substantial contribution of the oxidative (aerobic) system to the active metabolism during exercises of different duration.

Altitude training over a duration of 21-28 days at altitudes 2100-200 m above sea level is widely used in swimming in order to increase aerobic capacity, power and efficiency within definite periods of training macro cycles, including periods of preparation for major events. The content of individual training programs at altitude depends on the timing of altitude training within the macro cycle. Most frequently one of two variants of altitude training is used: 1) ‘intensive’ — with descent to sea level after altitude training 21-25 days before the major competitions and 2) ‘extensive’ — with descent 40-42 days before the major event. It should be mentioned here that both variants of altitude training have been used efficiently to maximise sport performance. Nevertheless, the 2nd variant is considered by many swimming specialists as much more safe, because training at altitude is predominantly aerobic and a block of high intensity race specific training is performed after descent to sea level instead.

The purpose of this study is to assess the effect of individual training programs on the dynamics of swimming velocity at the anaerobic threshold, \( \nu_0(\text{AT}) \), and the efficiency of swimming technique during a 21-day altitude training camp (altitude 1960 m, descent to sea level, 40-42 days before a
major swimming event). All of the swimmers who took part in the study specialised in 100 and 200 m events (Russian distance swimmers use a different training strategy).

**Methods**

In order to analyse the volume and intensity of the training workloads performed by swimmers during the camp, we used the original software «SwimPlanyzer». The software allows the recording and analysis of individual training programs according to seven training categories: Rec-F, EN1, EN2, EN3, SP1, SP2, SP3. For a more precise description of the training process we added the training category Rec-T which included a volume of exercises with targeted low aerobic pace, but performed with use of specialised snorkel device [3]. A combination of physiological (Kolmogorov et al. 2010) [4] and biomechanical methods (Kolmogorov 2008) [5] was used to assess the dynamics of \( v_0 (AT) \) in individuals at both the beginning and end of the altitude training camp. The subjects were 22 elite swimmers (14 males and 8 females).

In order to evaluate the efficiency of altitude training in every subject we measured the following metabolic criteria at the beginning and at the end of the training camp (see tables ‘A’):

- \( t_{200 (AT)} \) – time (sec) taken to complete a 200 meter lap of training set 6×200 m with a step-like intensity increase using # 1 stroke for which the athlete achieves the anaerobic threshold (AT)
- \( v_0 (AT) \) – swimming velocity (m s\(^{-1}\)) at which the athlete achieves AT
- \( VE \) – lung ventilation (l min\(^{-1}\)) at AT
- \( VO_2_{ck} \) –oxygen intake during swimming at AnT velocity above rest level (l min\(^{-1}\))
- \( RER \) – respiratory equivalent
- \( HR \) – heart rate during swimming at AnT (beats per min)
- \( Pai \) – power of active metabolism during swimming at AnT velocity (Watts)

The efficiency of individual swimming technique was assessed using a set of biomechanical characteristics [4, 5], registered at the beginning and at the end of the training camp (see tables ‘B’):

- \( v_0 (max) \) – maximal swimming velocity during a 30 meter lap (m s\(^{-1}\))
- \( Fp(t.) \) – average total propelling force generated by the swimmer in a swimming cycle (N)
- \( Pto \) – total external mechanical power (Watts)
- \( Fp(e.) \) – average effective propelling force generated by the swimmer in a swimming cycle (N)
- \( Puo \) – useful external mechanical power (Watts)
- \( ep \) – dimensionless coefficient of propulsive efficiency \( (ep = Puo/Pto) \)

**Results**

Average values of the total training volume, performed during the altitude training camp by 8 elite female and 14 elite male swimmers and their distribution into zones of training intensity illustrate very well the Russian concept for altitude training (table 1). The main objective of the altitude camp is the increase of power, capacity and efficiency of the aerobic energy system.
Table 1  Average values of the total training volume, performed during the altitude training camp by 14 elite male and 8 elite female swimmers and their distribution into zones of training intensity

<table>
<thead>
<tr>
<th></th>
<th>Male-swimmers</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Female-swimmers</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Standard Deviation</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>Standard Deviation</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male-swimmers</td>
<td>163.28</td>
<td>12.28</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>161.86</td>
<td>7.55</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>57.97</td>
<td>5.99</td>
<td>35.50%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>59.86</td>
<td>3.14</td>
<td>37.00%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>26.46</td>
<td>2.65</td>
<td>16.20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25.87</td>
<td>1.63</td>
<td>16.00%</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>33.11</td>
<td>2.39</td>
<td>20.28%</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>32.77</td>
<td>1.88</td>
<td>20.20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>32.52</td>
<td>4.34</td>
<td>19.92%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>31.15</td>
<td>1.52</td>
<td>19.20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td>1.20</td>
<td>1.68%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.19</td>
<td>0.38</td>
<td>1.35%</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>0.14</td>
<td>0.28</td>
<td>0.09%</td>
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<td></td>
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<td></td>
<td>9.95</td>
<td>0.45</td>
<td>6.14%</td>
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<td>10.28</td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

Since the model of altitude training employed in our study suggests that development of anaerobic glycolytic abilities should occur during re-adaptation after descent to sea level, exercises related to SP1 and SP2 intensity zones were excluded from altitude training of all (but two) athletes. It should be stressed that all swimmers of both genders performed an adequate volume of high-speed work at altitude, employing short laps (exercises from training zone SP3).

It is well known that the efficiency of training programs depends not only on the quantitative characteristics of the total training workload performed during the altitude stint, but also upon the dynamics of those characteristics through the sequence of training micro cycles. Therefore, in order to obtain objective information about altitude training we placed in corresponding tables individual values of training workload performed by swimmers for each of three training weeks of altitude camp. Table 2 shows the main characteristics of the training program performed by elite swimmer F5, specialised in 200 m freestyle. Individual values of the metabolic and biomechanical criteria for swimmer F5 at the beginning (test 1) and at the end (test 2) of altitude training are presented in Table 3.
Analysis of individual data for swimmer F5 (tables 2-3) recorded at the beginning and end of the training camp shows that during the period of altitude training the subject significantly improved the lap time (by 9.83 s) and velocity (by 7.1%) for the test set at which AnT was achieved.

Metabolic characteristics also increased: lung ventilation at AT – by 17 l min⁻¹ (16.2%), oxygen intake—by 0.386 l min⁻¹, the power of metabolic output during swimming at AT velocity increased by 135.83 Watts. The values of these characteristics are in accord with the corresponding average values reported for elite female swimmers [4].

The analysis of biomechanical characteristics has demonstrated an increase in the maximal swimming velocity during the altitude camp of 1.5%. At the same time, the total propelling force decreased by 9.0 N and the effective propelling force decreased by 3N, while the total and effective mechanical power decreased by 13.9 Watts and 3.0 Watts respectively. As a result of such changes, the coefficient of propulsive efficiency increased from 0.69 to 0.75. The latter suggests that an increase in the biomechanical efficiency of the individual’s swimming movements had occurred during altitude training. Individual values of ep in this subject are within the broad range of values demonstrated by elite female swimmers [4]. We suggest that the main reasons of the substantial increase in swimming velocity at AT during period of altitude training are 1) significant increase of the power of active metabolism and 2) positive dynamics of the coefficient of propulsive efficiency. It follows, from the assessment of the individual training program for swimmer F5 using metabolic and biomechanical criteria, that altitude training for the subject was highly efficient. Table 4 shows the main characteristics of the training program, performed at altitude by the male swimmer M8, specialised in the 200 m freestyle event, while Table 5 shows the results of his metabolic and biomechanical testing at the beginning and at the end of the camp.

Table 4  Weekly and total swimming volume and their distribution into intensity zones for elite male swimmer M8 during the 3-week altitude training camp

<table>
<thead>
<tr>
<th>Training categories (intensities)</th>
<th>Week-1</th>
<th>Week-2</th>
<th>Week-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rec-F</td>
<td>17000</td>
<td>25000</td>
<td>21800</td>
</tr>
<tr>
<td>Rec-T</td>
<td>11700</td>
<td>11300</td>
<td>6200</td>
</tr>
<tr>
<td>EN-1</td>
<td>11000</td>
<td>11800</td>
<td>14900</td>
</tr>
<tr>
<td>EN-2</td>
<td>3900</td>
<td>13000</td>
<td>21800</td>
</tr>
<tr>
<td>EN-3</td>
<td></td>
<td></td>
<td>1900</td>
</tr>
<tr>
<td>SP-1</td>
<td>1200</td>
<td>4100</td>
<td>4100</td>
</tr>
<tr>
<td>SP-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total swimming Volume</td>
<td>44800</td>
<td>65200</td>
<td>70700</td>
</tr>
<tr>
<td>Total swimming Volume minus Volume in Rec-F</td>
<td>27800</td>
<td>40200</td>
<td>48900</td>
</tr>
</tbody>
</table>
Comparison of test results for swimmer M8 at the beginning and at the end of altitude training camp (Table 5) has shown that during that training period he had improved the time (by 6.65 s) and velocity (by 5.2%) at AT during the swimming step-test 6x200 m.

VE at AT increased by 8.4%, oxygen intake increased by 0.435 l min⁻¹ and resulted in an increase (of 152.52 Watts) in the total metabolic power during swimming at that intensity.

At the same time, the maximal swimming velocity (by 0.043 m s⁻¹ or by 2.3%), the total propelling force (by 37.5 N or 26.7%) and the effective propelling force (by 17.7 N or 10.6%) were observed to decrease. The total and effective mechanical power decreased by 75.0 Watts (28.3%) and 37.0 Watts (20.9%) respectively. These changes resulted in an increase in the coefficient of propulsive efficiency from 0.67 to 0.74 (by 10.4%). Thus, despite minor decrease in maximal swimming velocity during the altitude camp, swimmer M8 demonstrated a substantial improvement in the biomechanical efficiency of his swimming technique. The value of his ep was within the higher range of values observed among elite male swimmers [4].

It follows from the analysis, that the significant improvement in the swimming velocity at AT during altitude training in swimmer M8 may be attributed to the increase in the total metabolic power accompanied by the positive change in the coefficient of propulsive efficiency. This indicates a positive outcome of the 3-week altitude training for the given athlete and the high efficiency of his training program.

Table 6 shows the main characteristics of the raining program, performed at altitude by the male swimmer M4, specialised in 100 m backstroke swimming. The results of his functional and biomechanical testing at the beginning and at the end of the camp are given in the Table 7.
Table 7 Characteristics of metabolism at AT level and biomechanical efficiency in elite male swimmer M4 (Height 1.83; Body Mass 73.0 kg) during backstroke swimming at the beginning and at the end of the 3-week altitude training camp.

<table>
<thead>
<tr>
<th></th>
<th>Criteria</th>
<th>$t_{200\text{(AT)}}$ (s)</th>
<th>$v_{0\text{(AT)}}$ (m s(^{-1}))</th>
<th>VE (l min(^{-1}))</th>
<th>$VO_2\text{ cle}$ (l min(^{-1}))</th>
<th>RER</th>
<th>HR (beats/min)</th>
<th>$P_a$ (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Test 1</td>
<td>145.45</td>
<td>1.347</td>
<td>125</td>
<td>3.640</td>
<td>1.00</td>
<td>166</td>
<td>1280.87</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>143.65</td>
<td>1.364</td>
<td>128</td>
<td>3.795</td>
<td>1.00</td>
<td>166</td>
<td>1335.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$v_{0\text{(max)}}$ (m s(^{-1}))</th>
<th>$F_{p(t.)}$ (N)</th>
<th>$P_{to}$ (Watts)</th>
<th>$F_{p(e.)}$ (N)</th>
<th>$P_{uo}$ (Watts)</th>
<th>$e_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Test 1</td>
<td>1.697</td>
<td>135.2</td>
<td>229.4</td>
<td>78.4</td>
<td>133.1</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>1.715</td>
<td>131.5</td>
<td>225.6</td>
<td>77.6</td>
<td>133.0</td>
</tr>
</tbody>
</table>

Subject M4 improved his performance over 200 m swam at AT velocity by 1.8 s and swimming velocity at AT by 0.018 m s\(^{-1}\) (1.3%) during the altitude training camp.

During altitude training, VE at AT increased by 2.4%, oxygen intake at AT swimming velocity rose by 0.155 l min\(^{-1}\) and the total metabolic power of swimming at AT velocity grew by 54.55 Watts. The maximal swimming velocity of M4 in the 30 m test increased by 1.1%. The main dynamic characteristics of swimming technique also changed: the total and effective propelling force decreased by 3.7 N and 0.8 N respectively. In turn, these changes caused an insignificant reduction of the total external mechanical power by 3.8 Watts, leaving the effective mechanical power unchanged (the coefficient of propulsive efficiency changed from 0.58 to 0.59). Individual values of $e_p$ in M4 were within the lower magnitude range for elite male swimmers [4].

The very small increase in the swimming velocity at AT for this subject with respect those observed in other swimmers is a result of an insignificant gain in the total metabolic power at AT and the minimal increase in the coefficient of propulsive efficiency. Thus, individual evaluation of the training outcome for subject M4 based on metabolic and biomechanical criteria has shown the low efficiency of the training program. Minor positive changes in the metabolic power and propulsive efficiency found in M4 were below the values recorded for other swimmers exposed to altitude training by a significant margin.

Conclusions

The study suggests that an objective judgment concerning the efficiency of individual altitude training programs should be based upon the simultaneous assessment of metabolic and biomechanical criteria. The bespoke altitude training not only increases the power of the oxidative energy system, but also significantly improves the biomechanical efficiency of swimming technique.

References


Visual search behaviour and information extraction differences between high-level and developing swimming coaches

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¹School of Sport Science, Exercise and Health, University of Western Australia

Keywords: coaching, expertise, eye-tracking, visual search behaviour, perceptual skills, technique assessment

Introduction

In swimming, where developing efficient technique is integral to achieving the main goal of swimming faster [1], a coach’s ability to diagnose the strengths and weaknesses of an athlete’s performance is critical for optimal development of the athlete. This relies on having a high-level of perceptual-cognitive skill that enables coaches to integrate visual information with existing knowledge ensuring the right decision concerning a swimmer’s technique can be made. A critical element of this is knowing where and when to look while observing a performance [2]. Despite this, information pertaining to the understanding of visual perceptual skills in swimming coaching is limited and it is unclear whether expert swimming coaches have developed visual search strategies that enable them to be more efficient at the way they extract and use visual information. While the visual perceptual skill of an athlete has been shown to be an indicator of expertise evidence supporting the idea of an expert coach also having superior visual perceptual skills is inconclusive.

Recording of the coach’s eye movements while watching a performance enables a direct evaluation of what aspects of the performance the coach is looking at. The location of a gaze fixation identifies an area of interest and the number and duration of fixations reflects the amount of information processed [3]. Of the limited research, however, the results are varied and a common visual search characteristic could not be established for expert coaches across a variety of sports. Some studies have found that expert coaches display a smaller number of fixations of longer duration [4, 5], while others have found no differences between expertise groups [6, 7]. In swimming, Moreno, Saavedra, Sabido and Luis [8] found no differences in the number, location or duration of fixations between swimming coaches of high and low levels of experience.

It is important to recognise that the limitation associated with relying on visual fixation data alone. Essentially, the studies mentioned above only reported what the subjects were looking at, and not what information was extracted from the visual environment. Without this information, it is not possible to critically assess the significance of the visual search behaviours of the coaches. Given that accumulation and organisation of knowledge specific to their field is a component that underpins an expert’s performance [9], and experts are able to represent problems in terms of their theoretical foundations whereas non-expert’s only view a problem’s surface aspects [10], it is logical that visual search behaviour would be influenced by the amount of knowledge and experience one has. How this relationship works, however, remains inconclusive and warrants further investigation.

Therefore, this study sought to investigate whether expert coaches with greater than 10 years of experience would have a different visual search strategy that enable them to extract greater amount of technical information when viewing a short video clip of a swimmer performing a freestyle sprint. More specifically, this study hypothesised that expert coaches will be able to extract a larger amount of information of greater depth than their developing counterparts, and would be more accurate at predicting the swimmers’ ability (swim time) than developing coaches. They would achieve this by relying on fewer gaze fixations that are of longer durations than that of developing counterparts.

Method and procedures

Participants were four expert and four developing professional swimming coaches from various swimming clubs in the Perth metropolitan area. In this study, expert coaches were required to have at
least ten years of coaching experience [6, 11], hold at least a silver Australian Swimming Coaches and Teachers Association Coaching (ASCTA) License (or equivalent), and have coached swimmers to National competitions in the past year. Given the highly specialised nature of this classification, the small number of expert coaches in this study represents a significant percentage of expert coaches in the state of Western Australia. The developing coaches had to hold at least a bronze (ASCTA) coaching license and have been coaching for no more than five years. Other factors such as experience with video analysis were also considered in the allocation process [8].

Coaches were fitted with the ASL Mobile Eye tracking system (Applied Science Laboratories, Bedford, MA) (Figure 1) and set-up in a seated position 5 m from large projector screen (Figure 2). Each participant watched twenty, 5 second video clips of a swimmer performing freestyle at maximum intensity; ten above and ten underwater clips. The above water clips were shown before the underwater. After each video the participant was asked to provide verbal responses to the following questions:

1. How fast would that person swim 50 metres freestyle?
2. Comment on that swimmer’s technique. Be as specific as you can, include the positive and negative aspects.

The swimmers filmed for the video clips ranged from elite (finalists at the Australian Championships) to Western Australian State Championships qualifiers. Swimmers were filmed while swimming one length of a 25 m swimming pool at a maximum effort from a push start. Each sprint effort was filmed in the sagittal plane above and below the water’s surface simultaneously using a custom-built filming system.

For each trial, the number, duration and location of fixations were recorded. A fixation was considered when a gaze fixed at a specific location for at least 100ms. For each participant, the average number of fixations and the average duration of fixations across all trials were calculated.

Verbal responses to question two were recorded and coded each time a coach mentioned one of the 15 stroke features most commonly associated with freestyle swimming. This protocol followed the framework developed by Chi and Leas [1]. These 15 features fall under the major technique components of body position, arms, kick and breathing. An additional scoring system was also created to recognise any ‘linking statements’ made by participants. One linkage was recorded for every connection made, for example a statement linking two locations was one linkage and a statement linking three locations was two linkages. These linked comments demonstrate an ability to identify associations between problem areas (and potential cause) and reflect a higher level of interpretation. Mean scores were calculated for each participant and each group.
Due to the small sample size, Cohen's $d$ effect sizes were calculated to interpret the meaningfulness of results. A large effect size was accepted at $d > 0.7$ and moderate effect size was accepted at $d > 0.4$.

**Results and discussion**

**Verbal responses**

Assessment of the verbal responses revealed that the expert coaches made a slightly higher number of comments specific to the 15 key stroke features in both above and underwater conditions (ES: $d = 0.40$ & $0.52$ for above and underwater viewing angles, respectively) (Figure 3). The moderate effect size might suggest that these differences should be taken conservatively. More importantly, the expert coaches made more linking statements in both above and underwater conditions (ES: $d = 1.73$ & $0.74$ for above and underwater viewing angles, respectively) (Figure 4). A linking statement refers to a statement that identifies several different stroke features in association with one another. The higher number of linking statements made by the expert coaches suggested that expert coaches had a greater understanding of the freestyle technique and how movement of one body part can affect the movement of another and the overall freestyle technique. This reflects the larger amount of procedural knowledge that expert coaches develop over years of experience [12, 13].

The fact that only small differences were found in the numbers of non-linking comments was of secondary importance. Firstly, the researchers took a conservative approach (no probing questions) while questioning the participants, and thus were not trying to extract as much information as possible out of the participants. Additionally, it could be speculated that expert coaches were better at reporting the essential information that will have the most impact on a swimmer’s performance. Nonetheless, the differences found in the verbal response section of this study support the idea that experts were displaying their larger knowledge base of the technical aspects of swimming freestyle.

**Determining ability (predicting 50m time)**

As well as providing feedback on the technique, coaches were also asked to estimate the 50m sprint time of each swimmer based on the 5s footage. It was hypothesised that experts would be more accurate in this task. Despite evidence from previous literature supporting this hypothesis [1, 14], the results showed no difference between the expert and developing coaches’ ability to determine the swimmers’ 50m freestyle times (Figure 5). Previous studies assert that the higher level of accuracy displayed by experts was due to better interpretation of incoming visual information. However, it is likely that predicting swim time from a 5s footage could be too novel a task and did not properly assess their skill in determining ability. There are other aspects which play a role in a swimmer’s performance and resulting time. Their physiological, cognitive and emotional components of performance all contribute [15]. For a coach to predict a swimmer’s 50m freestyle time they may
have been taking these other aspects into account and is therefore a poor indicator of how the coach is using their technical knowledge, because other components may be making an immeasurable contribution.

![Figure 5](image)

**Figure 5**  Mean absolute error for predicting 50m freestyle time (+ standard error) for above and underwater angles

**Visual search strategy**

The results from this study did not support the hypothesis that expert coaches would present a more efficient visual search strategy by having fewer gaze fixations that are of longer durations. This hypothesis was supported by previous research into motor and coaching expertise where the expert group had, on average, a lower number of fixations and these fixations were of longer duration [4, 16]. The expert group displayed a higher number of fixations that were of shorter duration than the developing group for both above and underwater angles (ES: $d > 0.70$ for all conditions). While these results contradict the hypothesis, it is unlikely that the expert coaches had a less efficient visual search strategy. On the contrary, the video assessment task required the coaches to extract as much information as possible in a short amount of time and the greater number of fixations by the expert coaches could mean that they were able to perceive the required information at each fixation location quicker and were therefore able to take in information from more locations for each trial.

![Figure 6](image)

**Figure 6**  Mean number of fixations for above and underwater angles (+standard error). ** denotes large effect size ($d>0.70$)

![Figure 7](image)

**Figure 7**  Mean duration of fixations for above and underwater angles (+standard error). ** denotes large effect size ($d>0.70$)
Conclusion

This study demonstrated that there could be a relationship between visual perceptual skill, information extraction and expertise in swimming coaching, a connection previously unstudied as a cohesive concept. In this study, expert and developing coaches displayed different visual search strategies, with experts exhibiting more visual fixations which enable them to extract more information than their developing counterpart. This study established the importance of visual perceptual skills in swimming coaching expertise and its connection with information extraction. Despite a conservative approach, experts displayed greater amounts of information extraction by making more verbal statements and, most importantly, displayed a deeper level of understanding by making significantly more linking statements.

Future research into swimming coaches’ visual perceptual skills could explore possible changes in visual search strategies when the demands of the task change. It is possible that the number of fixations and fixation duration could vary depending on the context of the task being performed and the experts could adapt and change strategies to maximise performance.

This study adds to the growing body of literature on coaching expertise, it supports previous literature in that experts have larger and more developed knowledge bases [1, 14]. This is the first study to establish a connection between visual perceptual skill and information extraction in terms of verbal responses and swimming coaching expertise.

References

4 Computational fluid dynamics

Torque and power about the joints of the arm during the freestyle stroke

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Abstract

Improvement of swimming performance involves changes to technique, endurance and strength, but the relationship between these factors cannot be predicted precisely for an individual athlete. Recent advances in computational models of swimming provide the opportunity to study these relationships in a virtual environment. Unlike in physical experimentation, the forces on individual body segments, torque about body joints and joint powers can be calculated in the model. These model outputs allow new insight into the loading on the body from the fluid along with the internal biomechanical forces that result. We use a coupled Biomechanical-Smoothed Particle Hydrodynamics (B-SPH) model to calculate joint torque and joint powers for the arms of a male elite athlete performing a freestyle stroke. Results show the large demand on the muscles of the arm, especially those spanning the shoulder. Future developments and applications of the model are discussed.

Introduction

Competitive swimming involves a complicated interplay between athlete strength and technique and the response of the water to the movement of the athlete. Unlike land based sports, where loading from the ground can be measured and used to estimate muscular exertion, it is practically impossible to measure loading on the body from the water and deduce muscular effort. It is not known precisely how modified strength or endurance attributes affect the performance of an athlete, nor is it known how this relationship varies with modified technique or between athletes. Knowledge of the dependence of joint torque and joint power on changes to stroke technique and athlete anthropometry would provide a valuable basis to understand the relationship between muscular effort and performance during competitive swimming.

Computational models of swimming have recently been shown to successfully predict fluid and athlete behaviour during swimming, despite the significant challenges in simulating this environment (Cleary et al. 2013; Cohen et al. 2012). Traditional computational fluid dynamics (CFD) modelling techniques are not well suited to predicting the interactions between moving bodies in water or the behaviour of the surface of the water. Recent progress in this area is attributable in part to the development of methods that can simulate each of the aspects of the physical environment of swimming. Smoothed particle hydrodynamics (SPH) is a method that is especially well suited to modelling the moving and deforming shape of the swimmer’s skin surface and the dynamic interactions with the splashing fluid.

In this study we use a coupled Biomechanical-Smoothed Particle Hydrodynamics (B-SPH) model of swimming to calculate the torques and powers generated about the joint of the arm by an elite male athlete performing a freestyle stroke. The athlete is represented in the model by a three-dimensional mesh that moves and deforms in a manner that matches video footage captured by three synchronised cameras. The SPH method is applied to calculate the response of the fluid to the swimmer and the forces across the surface of the body. A biomechanical model of the body joints is used to calculate the torque about each joint throughout the stroke cycle. Power is calculated from...
the net work done by the muscles about each joint to generate torque. The results of the model provide new insight into the muscular effort required to perform the freestyle stroke.

**Method**

The computational model comprises an SPH model of water dynamics, coupled to a biomechanical model of the swimming athlete. The SPH model predicts the response of the water to interactions from the moving swimmer and the forces imparted onto the athlete’s body from these interactions. The biomechanical model of the athlete includes a representation of the surface of the body, which moves and deforms in response to motion of the joints. The coupling between these models allows the calculation of forces on each body segment and the torque and power generated by each joint of the body.

**Numerical modelling of fluid dynamics using SPH**

SPH is a numerical method that is well suited to modelling swimming athletes because it can easily simulate interactions between water and moving and deforming bodies and splashing of water, each of which are very difficult to accurately represent using conventional, grid-based computational fluid dynamics methods. More generally, SPH is a mesh-free Lagrangian particle method for solving partial differential equations. Fluid dynamics applications of the method are detailed in Monaghan (1994), Monaghan (2005) and Cleary et al. (2007). Volumes of fluid are represented by a moving set of particles, over which the Navier-Stokes equations can be reduced to numerically solvable ordinary differential equations. A coupled biomechanical–smoothed particle hydrodynamics (B-SPH) model has been used to gain new insights into injury risk in platform diving (Harrison et al. 2012a), and performance during kayaking (Harrison et al. 2012b), dolphin kick swimming (Cohen et al. 2012) and freestyle swimming (Cleary et al. 2013).

**Biomechanical model of the swimming athlete**

The surface of the athlete’s body is represented in the simulation by a three dimensional mesh which moves and deforms in a manner that matches video footage of an individual elite athlete. The mesh is rigged to a virtual skeleton using the dual quaternion method (Kavan et al. 2008) such that the nodes of the mesh move in response to the motions of one or more bones, resulting in realistic deformations of the mesh surface. The virtual skeleton comprises 23 spherical joints, including representations of the ankles, knees, hips, shoulders, elbows, wrists, spinal column and neck. Any pose of the athlete’s body can be successfully represented in the model by manipulation of the three joint angles of each of the skeletal joints.

The motion of the swimming athlete was digitised from video footage of a freestyle stroke. Details of the digitisation method are given in Cohen et al. (2014). One complete stroke cycle was used in the simulation. The period of the stroke was 1.32 s and the mean speed was 1.75 m/s. The digitised motion of the athlete is shown in Figure 1. The left side catch and pull phases occur at the time in period \( t / T \) 0.75 to 0.30 and the right side catch and pull phases occur for \( t / T \) from 0.25 to 0.65.

Joint torques and joint powers were calculated from the fluid forces calculated on each node of the surface mesh representing the athlete. The net fluid force on each body segment (e.g. hand, forearm, head or thigh), \( f_{\text{segment}} \), was calculated as the sum of fluid forces on nodes of the segment, \( f_i \):

\[
f_{\text{segment}} = \sum_{i=1}^{N} f_i
\]

where \( N \) is the number of nodes on the \( ith \) body segment.
The torque about the $i$th joint, $\mathbf{M}_i$ (e.g. elbow) was calculated as the sum of torques from the fluid forces on the distal body segment (forearm), plus the torque about any distal joints (wrist):

$$\sum_{i=1}^{N} \mathbf{s}_i \times \mathbf{f}_{\text{segment}} = \sum_{j=1}^{Q} \mathbf{R}_j \Theta_j \mathbf{R}'_j$$

where $\mathbf{s}_i$ is the position vector of the mesh node in the joint reference frame, $\mathbf{R}_j$ is the 4x4 transformation matrix from the reference frame of the $i$th joint to its $j$th distal joint, $Q$ is the number of distal joints and the action, $\Theta_i$, on each joint is a skew-symmetric matrix of the net torques $\mathbf{M} = (M_x, M_y, M_z)$ and net forces $\mathbf{F} = (F_x, F_y, F_z)$ on the joint:

$$\Theta_i = \begin{bmatrix} 0 & -M_z & M_y & F_x \\ M_z & 0 & -M_x & F_y \\ -M_y & M_x & 0 & F_z \\ -F_x & -F_y & -F_z & 0 \end{bmatrix}$$

The power about the $i$th joint, $P_i$ is equal to the dot product of the joint torque, $\mathbf{M}_i$, and the angular rotation of the joint, $\theta_i$:

$$P_i = \mathbf{M}_i \cdot \theta_i$$

Joint power, joint torque and segment force results were temporally normalised to the period of the stroke.

**Results and discussion**

Figure 2 shows the response of the water to the motion of the athlete and the net fluid force on each arm at four times during the stroke cycle. At the start of the right catch (Figure 2a) the arm moves downward in the water and the water imposes drag and buoyancy forces upwards on the arm. Midway through the pull phase (Figure 2b) the arm moves downward and backward and the resulting force on the arm is orientated slightly forwards, providing propulsion to the body. At the start of the push phase (Figure 2c), the force on the arm is orientated completely forwards, providing a larger
level of propulsion. At the end of the pull phase the arm moves upwards against the water and forces reduce in magnitude and are orientated primarily downwards.

Figure 2  Visualisation of the athlete motion, water surface and net arm force at (a) the start of the catch phase, (b) mid catch, (c) the beginning of the pull phase and (d) the end of the pull phase of the right arm stroke.

Magnitudes of torque about the arm joints are shown in Figure 2. Torque is approximately zero during the recovery phase and small, but non-zero in the entry phase. Large peaks are visible approximately at the middle of each of the pull and push phases (see also Figure 1 to reference timing of the stroke phases). Torque peaks are large for each joint (Bober et al. 2002) and of greater magnitude for the proximal joints: wrist torques peak at 17 Nm, elbow torques peak at 85 Nm and shoulder torques peak at 176 Nm. Time averaged torques are also approximately an order larger for the shoulder than for the wrist (Table 1). These results show the large range of demand on muscle groups through the arm, specifically the shoulder muscles are required to generate ten times the torque of the muscles spanning the wrist.
Joint powers are plotted in Figure 3. As for the results of joint torque, the power is negligible during the recovery phase and small in the entry phase. Large variations in power occur during the catch and pull phases due to the combination of variations in joint angular velocity and the previously observed variations in joint torque (see Equation 7 and Figure 2). Peaks in power also generally decrease in magnitude with distance along the arm from the proximal joint (shoulder, 20 – 29 W) to the intermediate joint (elbow, 4.5 – 5.2 W) and the distal joint (wrist 2.3 – 6.5 W). The total work done by each joint is also shown in Table 1. Whilst the torque at the elbow is generally much larger than at the wrist, the wrist is rotated more than the elbow during the catch phase of the stroke, meaning that the work done by the wrist and elbow are similar in magnitude. Angular rotation of the shoulder is large and so the work done by the shoulder joint is five times larger than the elbow or wrist. Maintaining this level of work at the shoulder not only requires strength, but also endurance in the muscles spanning the joint. Comparison of these results with strokes at different speeds and with varied
athletes will provide further insights into the strength and endurance requirements of freestyle stroke at an elite level.

**Future work**

The methods used this study have a potential to inform technique and conditioning training for the range of swimming strokes. Using a larger data set of digitised athlete motions, the relationship between performance and muscle exertion can be determined. Using this approach the dependence of joint torque and power on the following variables can be explored:

- stroke speed (training speed through to racing speed),
- intra-subject variability for the same speed and stroke,
- inter-subject variability for the same speed and stroke, and
- inter-stroke variability.

This data would inform strength and conditioning training for desired performance outcomes. Validation of model outputs to measurable quantities and analyses of model sensitivity to inputs and configurations, such as particle resolution, will also be explored.

It is worth noting that calculations of joint torque and power do not directly predict magnitudes of muscle force and power, the latter of which are better measures of exertion. Future work with the model will involve incorporating muscle models (Anderson & Pandy 2001) to calculate muscle, tendon and ligament forces and muscle work. Forward dynamics simulations will be constructed, in which performance changes due to increases in muscle strength or endurance can be directly predicted.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Average Torque (N)</th>
<th>Work done (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>Wrist</td>
<td>5.4</td>
<td>5.0</td>
</tr>
<tr>
<td>Elbow</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>Shoulder</td>
<td>46</td>
<td>43</td>
</tr>
</tbody>
</table>

As with applications of the modelling framework to other sports (Harrison et al. 2012a), injury risks can also be evaluated by investigation in the magnitudes of joint torque and forces in muscle, tendon and ligaments. The relationship between stroke technique and possibly injurious loading can be indentified and used to inform mitigation strategies.

**Conclusions**

The study details the first coupled biomechanical-computational fluid dynamics model able to calculate joint torques and joint powers in a simulation of swimming. The model outputs allow the evaluation of strength and endurance demands on muscle groups of the body throughout the stroke cycle. Torque demands were large in reference to other activities and the magnitude of torque increases from the distal to proximal arm joints. Peaks in torque were seen in both the catch and pull phases and torque was small during entry and approximately zero during recovery. Arm joint power showed a similar trend, albeit with more variation due to changes in joint angular velocity. Future applications to modified stroke styles, other strokes and other athletes will further elucidate the relationship between technique, muscular effort, endurance and the resulting performance of the elite athlete.
References


An analysis of a swimmer’s passive wave resistance using experimental data and CFD simulations

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Introduction

The passive resistance of a swimmer on the free surface has previously been researched experimentally. The contribution of wave resistance to total drag for a swimmer with a velocity around 2.0 m.s⁻¹ was found to vary from 5% for Vorontsov and Rumyantsev (2000), to 21% for Toussaint et al. (2002) and up to 60% according to Vennell et al. (2006). The exact resistance breakdown of a swimmer remains unknown due to difficulties in the direct measurement of wave resistance. As noted by Sato and Hino (2010), this lack of experimental data makes it difficult to validate numerical simulations of swimmers on the free surface.

This study is therefore aimed at presenting direct measurements of a swimmer’s total drag and wave resistance, along with the longitudinal wave cuts which may be used to validate numerical simulations. In this paper, experimental data of a swimmer’s resistance are presented at two different velocities (case 1 = 1.7 m.s⁻¹ and case 2 = 2.1 m.s⁻¹). Total drag was measured using force block dynamometers mounted on a custom-built tow rig (Webb et al. 2011). Moreover, a longitudinal wave cut method was used to directly evaluate wave resistance (Eggers 1955).

The two conditions tested were simulated using the open-source Computational Fluid Dynamics (CFD) code OpenFOAM (OpenFOAM® (2013)). The body geometry is a generic human form, morphed into the correct attitude and depth using the above- and under-water video footage recorded during the experiment. 3D Unsteady Reynolds-Averaged Navier-Stokes (URANS) simulations were performed using the Volume of Fluid (VOF) method to solve the air-water interface. A similar numerical technique was used by Banks (2013a) to assess the passive resistance of a swimmer. Two cases were
simulated and the error in total drag compared to the experimental data was found to be 1% and 22% respectively. In this paper, the resistance components over a swimmer’s typical range of speeds are investigated and compared with the experimental data.

**Methods**

**Experimental set-up and analysis**

A male swimmer (height = 1.78 m, weight = 66 kg) was towed passively along a 25-m pool, with their arms by their side, with a tow belt fixed around his waist. Two speeds were chosen across the range of typical swimming speeds: 1.7 m.s\(^{-1}\) (case 1) and 2.1 m.s\(^{-1}\) (case 2). Both total resistance and wave resistance were measured. The experimental set-up is presented in Figure 1.

![Figure 1](image.png)

**Schematic of the University of Southampton Jubilee swimming pool with infinity edges**

The total resistance was obtained by averaging data from the force-block dynamometers mounted on a custom-built tow winch. The instrumented tow system allows the swimmer to be pulled along the pool at a constant speed whilst the tow force is measured using three force blocks (Webb et al. 2011). The magnitude of the measured force is calibrated at the beginning of each session by applying a known force to the system. A moving camera allows a synchronised video feed to be acquired at the same time.

The wave pattern resistance was obtained using a longitudinal wave cut method originally defined by Eggers (1955), developed by Insel (1990) and refined by. This method assumes that a slender body is moving in an inviscid, incompressible and homogeneous fluid and that the resulting flow is steady and irrotational. Furthermore, the wave height should be significantly smaller than the wave length. A tripod was set halfway along the pool (x = 12.5 m) with an array of three wave probes located at distances y = 1.50, 1.75 and 2.00 m away from the track of the swimmer. These wave probes are made of two parallel stainless steel wires, 12 mm apart. The conductivity between air and water is significant enough that a change in voltage output can be measured as the water surface deforms. The probes were calibrated by acquiring the voltage output at two known immersion depths +/- 0.1 m as they have known linearity response.

During a run, three longitudinal wave cuts were recorded at a sample rate of 250 Hz. A numerical wave profile was fitted through each experimental wave cut and the matrix method developed by Insel (1990) was used to determine the Eggers coefficients \(\xi_{m}\) and \(\eta_{m}\), leading to the full wave system definition.

\[
\zeta = \sum_{m=0}^{M} \left[ \xi_{m} \cos(\psi_{m} \cos \theta_{m}) + \eta_{m} \sin(\psi_{m} \cos \theta_{m}) \right] \times \cos \frac{\pi y_{m}}{b}
\]
where, $\gamma_{n, m} = \frac{2\pi n}{b}$, $\hat{\theta}_m$ is the wave angle, $b$ is the width of the domain and $M$ is the number of harmonics.

Theoretically, only one longitudinal wave cut is necessary to evaluate the wave elevation, $\zeta$, but in case the term $\cos \frac{2\pi n}{b} \rightarrow 0$ for some harmonics, longitudinal wave cuts from the two wave probes closest to the swimmer were used for the analysis.

Once the Eggers coefficients are found, the wave resistance can be calculated as follows:

$$R_w = \frac{1}{4} \rho g b \left\{ \left( \xi_0^2 + \eta_0^2 \right) + \sum_{n=1}^{M} \left( \xi_n^2 + \eta_n^2 \right) \left( 1 - \frac{1}{2} \cos^2 \theta_n \right) \right\}$$

**Computational fluid dynamics**

**Swimmer geometry**

A generic body scan of a human with their arms by their sides was used as a basis athlete geometry. The basis athlete geometry was modified with an in-house meshing tool called Adaptflexi (Turnock 2004) so as to match the different case conditions. This has the capability to take a .STL geometry and deform it in a number of different ways. Firstly, variable scale factors are applied along the body to match a specific athlete’s body shape. Secondly, joint rotations are performed to match the athlete’s attitude and posture from the video footages acquired during the experiment (Figure 2).

![Swimmer’s position from the under-water view used to modify a generic scanned body](image)

**Meshing technique**

An unstructured hexahedral mesh around the swimmer was created using the snappyHexMesh utility within the open source CFD package OpenFOAM-2.2.0 (OpenFOAM® 2013). First, a coarse block mesh with dimensions $14 \times 7.5 \times 2$ [m$^3$] was created with cells of $0.2$ m in each direction. Regions were defined with up to six levels of isotropic refinement (recursively having in all three local cell dimensions six times), gradually increasing the mesh density near the body, whilst maintaining a cell aspect ratio of approximately one. Unidirectional refinement was applied perpendicular to the free surface to provide good wave pattern resolution, whilst minimising mesh size. Boundary layer elements were grown out from the body surface mesh to provide a $y^+$ of 1. This places approximately 10 cells within an estimated $y^+$ of 40 allowing the viscous boundary layer to be captured (WS Atkins Consultants 2003). The developed mesh structure contains approximately eight million elements and is shown in side elevation and plan view (Figure 3).
Numerical approach with the inclusion of a free-surface

The fluid properties around the swimmer were solved with the Unsteady incompressible Reynolds-Averaged Navier-Stokes (URANS) equations using a second order PISO finite volume method. The fluid temperature was set to 25°C with a density of 997 kg.m$^{-3}$ and a kinematic viscosity of $0.89 \times 10^{-6}$ m$^2$.s$^{-1}$. The k-ω SST turbulence model was applied since it provides a reasonable representation of a boundary layer under adverse pressure gradients, separation and recirculation. A Volume of Fluid (VOF) approach was used for the free surface with the volume fraction transport equation defined as:

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\phi \mathbf{U}) = 0$$

where \( \phi \) is the volume fraction calculated as the volume ratio of water to air in a given cell (Peric, M. & Ferziger 2002). The fluid density, \( \rho \), and viscosity, \( \mu \), can then be respectively calculated as:

$$\rho = \rho_{air}(1-\phi) + \rho_{water}\phi \quad \text{and} \quad \mu = \mu_{air}(1-\phi) + \mu_{water}\phi$$

The detailed numerical settings used to perform the multi-phase simulations discussed in this paper can be found for similar simulations in Banks (2013b). These simulations were computed in parallel runs on the high performance computing facility available at the University of Southampton Iridis 4 (10x16 core nodes each with 4GB RAM/core). At the lowest speed, seven hours were required to simulate one second of real time and the simulations were run for 25 seconds in order to capture three flows through the domain.

Results

The wave fields observed around the swimmer during the experimental tests and as obtained from CFD are presented in Figure 4 and 5. At the higher speed (case 2 – \( V = 2.1 \) m.s$^{-1}$), more energy is transferred to the wave system resulting in a larger-amplitude wave pattern. Consequently, a higher wave resistance is obtained in this case as indicated in Table 1 (on average 26% increase between case 1 and case 2).
Case 1 \(-V = 1.7 \text{ m.s}^{-1} - F_n = 0.38\)

Case 2 \(-V = 2.1 \text{ m.s}^{-1} - F_n = 0.49\)

Note: Free surface deformation displayed with contours ±0.01m (bold contours are wave trough) and longitudinal wave cuts positioned at \(y = 1.50, 1.75\) and \(2.00\) m away from the swimmer (c).

**Figure 4**  A comparison of the wave pattern observed around the swimmer during the experimental tests (a) with the numerical solution (b, c) of the free surface.

**Figure 5**  A comparison of the experimental and numerical longitudinal wave cuts at different offset distances \(y\) from the centerline (Case 1 (left) and Case 2 (right)).

As presented in Tables 1 and 2, the total swimmer’s passive resistance breaks down to the sum of the skin friction and pressure force. This last term can be further expressed in terms of the viscous pressure form and the wave drag. The CFD skin friction and total pressure force were obtained by taking the average values of two steady flows through.

The experimental data evaluated using the methodology described in 2.1 confirms a higher wave resistance at the highest speed; however the percentage of drag due to wave resistance increases as the speed decreases. Averaging the data over three repeat runs, wave resistance represents 13.7% of
the total drag at 1.7 m.s\(^{-1}\), whereas at the higher average speed tested of 2.1 m.s\(^{-1}\), wave resistance accounts for only 11.5% of the total drag.

### Table 1  Case 1 (Speed = 1.7 m.s\(^{-1}\)) – Measured values

<table>
<thead>
<tr>
<th>Resistance [N]</th>
<th>ITTC’57 coeff. (ITTC 2002)</th>
<th>Experiment</th>
<th>CFD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Force [N]</td>
<td>% R, Coeff. [-]</td>
</tr>
<tr>
<td>Skin friction</td>
<td></td>
<td>3.61E-03</td>
<td>10.43</td>
</tr>
<tr>
<td>Pressure</td>
<td>P-viscous (form)</td>
<td>18.07, 14.68, -</td>
<td>86.58</td>
</tr>
<tr>
<td></td>
<td>P-wave</td>
<td></td>
<td>97.01</td>
</tr>
<tr>
<td></td>
<td>P-total (P-v + P-w)</td>
<td>120.1, 119.7, 118.3</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2  Case 2 (Speed = 2.1 m.s\(^{-1}\)) – Measured values

<table>
<thead>
<tr>
<th>Resistance [N]</th>
<th>ITTC’57 coeff. (ITTC 2002)</th>
<th>Experiment</th>
<th>CFD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Force [N]</td>
<td>% R, Coeff. [-]</td>
</tr>
<tr>
<td>Skin friction</td>
<td></td>
<td>3.45E-03</td>
<td>16.86</td>
</tr>
<tr>
<td>Pressure</td>
<td>P-viscous (form)</td>
<td>17.21, 24.90, 23.41</td>
<td>132.98</td>
</tr>
<tr>
<td></td>
<td>P-wave</td>
<td></td>
<td>149.84</td>
</tr>
<tr>
<td></td>
<td>P-total (P-v + P-w)</td>
<td>183.4, 195.3, 193.1</td>
<td></td>
</tr>
</tbody>
</table>

### Discussion

The numerical simulation effectively captured the wave system developed by the swimmer in a comparable manner to the experiment, as seen in Figure 5. Overall, there is a better agreement with the wave probe located closer to the swimmer and for the near-wake.

The discrepancy between the numerically simulated free surface elevation and the measured longitudinal wave cuts comes from several factors. In a pool, there is only a partial wall reflection, whereas in the CFD a solid boundary is simulated. Furthermore, during the experiment, the free surface was never perfectly calm, despite time being allowed for the pool water surface to settle. This may have caused small wave interactions resulting in different wave resistances over the experimental set of runs. Numerical diffusion may also cause the simulated wave pattern to dissipate further away from the swimmer.

Another major unknown is the variability in the swimmer’s position during a run. Indeed, a swimmer cannot physically adopt a steady position whilst being towed. His vertical position is governed by balancing the buoyancy, weight and hydrodynamic forces. His attitude in the water is dictated by the moments generated by these forces. For instance, the distance between the centres of buoyancy and gravity generates a moment which tends to pitch the feet down. Increase in a swimmer’s angle of attack leads to a larger frontal area, resulting in a higher drag as identified in Tables 1 and 2. As the fluid forces and moments acting on a swimmer’s body are unsteady, the athlete naturally controls his position in the water with small movements of his body, which are not captured in the simulations.

All these factors are currently not directly quantifiable but are known to have a significant impact on the various resistance components. It is noted that these variations can be seen in the recorded line tension and are averaged for each of the three repeat runs (the coefficient of variation is 6%). The ITTC (1967) resistance committee reported a study from Maruo and Ishii, which considered different underwater hull forms in the near free surface to reduce wave resistance. These results emphasise the substantial impact of a body volume and position near the free surface on the wave resistance.
The described sources of error can explain: the discrepancy between the numerical simulations and the experimental data, and the differences between repeated experimental runs.

Conclusions

To the authors’ knowledge, this paper presented the first direct measurements of the passive wave resistance of a swimmer with the use of a longitudinal wave cut and matrix analysis used in naval architecture. On average, wave resistance represents 13.7% of the total drag at 1.7 m.s⁻¹ and 11.5% of the total drag at 2.1 m.s⁻¹. It is important to note that these values are specific to the swimmer body geometry and position adopted during the experimental runs presented. More repeat runs of the same athlete and other athletes with different body geometries would be necessary to establish a relationship between body geometry and position with respect to the free surface and wave resistance.

The numerical simulations effectively captured the fundamental flow features of the wave system generated by the swimmer. However, a comprehensive validation of CFD simulations remains difficult because of human variability and discrepancies in the geometry. The uncertainties associated with towing a human swimmer would be alleviated through the use of a captive mannequin in a towing tank to ensure repeatable conditions, which can be more easily compared with the numerical simulations.

Acknowledgments

The authors would like to acknowledge the University of Southampton for the use of the supercomputer Iridis 4 and the PhD sponsors: EPSRC, English Institute of Sport, British Swimming and Speedo.

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Computational fluid dynamic analysis of streamlined gliding and freestyle kicking at different depths

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Keywords: computational fluid dynamics, streamlined glide, kicking, drag, propulsion

Abstract

Computational Fluid Dynamics (CFD) allows simulation of complex fluid flow regimes and geometry to overcome limitations with current empirical testing techniques. The CFD model can predict net propulsion or net drag of each body segment when gliding and kicking. Thus, one can determine the differences between the forces on body components at depth and the surface. This study aimed to predict how and where changes in net forces of a swimmer gliding and kicking at the water surface compared with being fully submerged. These analyses increased our technical understanding regarding net forces produced during gliding and freestyle kicking; and reported large differences in forces on various body components when fully submerged and at the air-water interface.

Introduction

There is a shift of emphasis within the coaching profession and researchers that greater benefits result from technique changes to reduce drag rather than aiming to increase velocity solely by increasing propulsion (Rushall et al. 1994). But, the complex interaction of forces on swimmers, and how they create propulsion and/or minimise active drag, remain unclear. Hence, increased knowledge of fluid flow forces and force production mechanisms in swimming is crucial for developing optimal techniques for individual swimmers, improved training protocols, faster times and decreased injuries.

Using basic fluid mechanics principles, CFD allows simulation of complex fluid flow regimes and geometry, and provides vision of resultant variables over the whole domain. Thus, CFD can measure variables such as velocity, acceleration and the propulsive and resistive forces acting totally, or on specific body segments of a swimmer. This can provide insight into problems not yet obtainable via known physical testing techniques, and has been identified as a key to future swimming technique developments.

CFD analyses have progressed since the initial investigation by Bixler and Schloder (1996), which used a disk of the same size as a human hand to estimate hand forces during the freestyle stroke. With improved technology, studies using CFD analysis have examined hand motion through the water (Sato & Hino 2002), hand and arm acceleration through the water (Rouboa et al. 2006), propulsion created by hand and forearm in steady flow (Bixler & Riewald 2002), effects of finger-spread on propulsion (Marinho et al. 2010) and underwater kicking (Lyttle & Keys 2006; Von Loebbecke et al. 2009).

Further, CFD analysis has progressed to a single case study of a full-body dynamic analysis of the complete freestyle stroke in an unsteady flow (Keys 2010).

Empirical testing of gliding and kicking, when underwater and at the water surface, found that total body net forces changed with depth (Lyttle et al. 1998, 2000). But, the studies could not determine...
whether the net force distribution changed across the body; which would indicate the differences created by changes in trailing vortices. While travelling underwater, the trailing vortices form a three dimensional vortex in any direction. However, at the water surface, the vortices will not form across phases (i.e the air/water interface) and a surface wave results.

This study used a full body dynamics CFD code (Keys 2010). Net force distribution across body segments when gliding and kicking underwater, and at the water surface, were examined. How these net propulsive and net drag forces interact across the body could increase greatly our understanding of swimming hydrodynamics.

**Methods**

The capabilities of CFD simulations for determining differences between a streamlined glide and freestyle kick, when submerged and closer to the surface, were gained via using a standard case study format. An elite swimmer was filmed performing underwater freestyle kicking at maximal effort from a sagittal view. A full 2D kinematic analysis was performed using manual digitising, due to the predominantly planar action of the freestyle kicking pattern, with results summarised in Table 1. The same freestyle kick kinematics was then applied to the surface swimming simulations.

<table>
<thead>
<tr>
<th>Derived Kinematic Variables</th>
<th>Left Leg</th>
<th>Right Leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kick Amplitude (vertical displacement of toe) (m)</td>
<td>0.57</td>
<td>0.53</td>
</tr>
<tr>
<td>Kick Frequency (Hz)</td>
<td>2.56</td>
<td>2.56</td>
</tr>
<tr>
<td>Minimum Hip Rotation (°)</td>
<td>169.4</td>
<td>169.8</td>
</tr>
<tr>
<td>Maximum Hip Rotation (°)</td>
<td>185.1</td>
<td>187.0</td>
</tr>
<tr>
<td>Minimum Knee Rotation (°)</td>
<td>147.0</td>
<td>140.2</td>
</tr>
<tr>
<td>Maximum Knee Rotation (°)</td>
<td>189.2</td>
<td>196.4</td>
</tr>
<tr>
<td>Minimum Ankle Rotation (°)</td>
<td>123.8</td>
<td>121.7</td>
</tr>
<tr>
<td>Maximum Ankle Rotation (°)</td>
<td>179.1</td>
<td>150.7</td>
</tr>
</tbody>
</table>

The 3D mapping of the swimmer used a Cyberware WBX whole body laser scanner with a density of one point every 4mm; with the swimmer wearing a full-length competition swimsuit in a streamlined glide position. The laser scan created a 3D superficial model of a swimmer within the order of a million surface points. Higher resolution scans also were conducted of the head, hands and feet (density of one point every 0.66mm). The higher resolutions were deemed important as these areas set the initial flow conditions (hands and head), and develop thrust (by the feet). The higher resolution scans were aligned and merged seamlessly into the full body scan to provide more accuracy at these locations. The 3D model was then processed to extract 288 non-uniform rational b-spline (NURBS) curved surfaces forming a 3D solid model of the swimmer.
The computer simulation used the CFD software package ‘FLUENT’ (ANSYS; version 6.1.22). In brief, the CFD finite volume technique involves creating a domain, inside which the flow simulation occurs; bounding the domain with appropriate external conditions, and breaking the domain up into a finite number of volumes or cells. The governing equations of fluid flow are then integrated over the control volumes of the solution domain. Finite difference approximations are substituted for the terms in the integrated equations which represent the flow processes. This converts the integral equations into a system of algebraic equations that are solved using iterative methods.

The CFD model was established using RANS Realisable k-epsilon turbulence model together with standard wall functions and second order discretisation, as was recommended as best practice for this type of simulation (Shih et al. 1995; Fluent 2004). The meshing located at the swimmer’s body surface for the near-wall boundary layer was optimised depending on the appropriate $y+$ value and allowable space and contained on average 3-5 layers of prism cells, with tetrahedral cells making up the remaining fluid zones. The Volume of Fluid Model Theory (Fluent 2004) was used for the air-water interface modelling in the near surface trials. Spring-based smoothing, in combination with localised re-meshing algorithms, was used for the dynamic mesh movement. User defined dynamic mesh functions were used for simulating the flexible and rigid motions of surface and mid-stream nodes. This occurred in combination with the three polar angles and eight co-efficient Fourier series equations for the motion of segments in the kicking simulations.

Two model depths were examined for both the streamlined glide and the freestyle kicking. In the fully submerged trials, the subject’s mid-iliac crest was located at 1.5m deep to limit any confinement effects, with a total modelled pool depth of 3m. The surface trials were conducted with the depth of the swimmer’s mid-iliac crest located 0.1m underwater.

An initial static CFD model run was performed at glide velocity of 2.00m.$s^{-1}$ with the swimmer in a streamlined glide position at both depths. The wave created around the body from the CFD modelling was then compared with properties obtained via Linear Wave Theory. Subsequently, a multi-phase domain, dynamic CFD analysis of the underwater freestyle kick simulation at 1.50m.$s^{-1}$ was compared with the same kicking patterns at the water surface. The set speed experiments for the CFD modelling were performed to allow the direct comparison of the same set of kinematics at the different depths. The selected freestyle kick simulation velocity matched the average velocity obtained from elite swimmers during short kick-only sets in training.
Results

Table 2 represents the passive drag force comparisons in Newtons (N). The output is broken down into the net drag and propulsion created by each individual component. Then, the following tables and figures show the analysis results for simulated freestyle kick at the different depths. Table 3 displays the culmination of momentum throughout the kick cycle and then averaged to a value per second value.

Table 2  Differences in passive drag on body components when fully submerged and at the surface

<table>
<thead>
<tr>
<th>Component</th>
<th>Submerged</th>
<th>Surface</th>
<th>Change</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m.s⁻¹)</td>
<td>2.00</td>
<td>2.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (N)</td>
<td>-50.64</td>
<td>-61.94</td>
<td>-11.30</td>
<td>-18.2%</td>
</tr>
<tr>
<td>Hands (N)</td>
<td>-5.13</td>
<td>-5.48</td>
<td>-0.35</td>
<td>-0.6%</td>
</tr>
<tr>
<td>Arms (N)</td>
<td>-22.68</td>
<td>-53.79</td>
<td>-31.11</td>
<td>-50.2%</td>
</tr>
<tr>
<td>Head (N)</td>
<td>-10.01</td>
<td>-37.27</td>
<td>-27.26</td>
<td>-44.0%</td>
</tr>
<tr>
<td>Upper Body (N)</td>
<td>-6.14</td>
<td>-22.82</td>
<td>-16.68</td>
<td>-26.9%</td>
</tr>
<tr>
<td>Total-Body (N)</td>
<td>-43.96</td>
<td>-119.37</td>
<td>-75.40</td>
<td>-121.7%</td>
</tr>
<tr>
<td>Hips (N)</td>
<td>-2.63</td>
<td>-3.47</td>
<td>-0.84</td>
<td>-1.4%</td>
</tr>
<tr>
<td>Thighs (N)</td>
<td>3.13</td>
<td>42.90</td>
<td>39.77</td>
<td>64.2%</td>
</tr>
<tr>
<td>Knees (N)</td>
<td>2.06</td>
<td>12.72</td>
<td>10.67</td>
<td>17.2%</td>
</tr>
<tr>
<td>Calves (N)</td>
<td>1.97</td>
<td>6.10</td>
<td>4.13</td>
<td>6.7%</td>
</tr>
<tr>
<td>Ankles (N)</td>
<td>-4.47</td>
<td>-11.97</td>
<td>-7.49</td>
<td>-12.1%</td>
</tr>
<tr>
<td>Feet (N)</td>
<td>-6.73</td>
<td>11.14</td>
<td>17.87</td>
<td>28.9%</td>
</tr>
</tbody>
</table>

Table 3  Differences in momentum per second (Ns/s) created for submerged and surface simulations.

<table>
<thead>
<tr>
<th>Component</th>
<th>Freestyle Kick - Submerged</th>
<th>Freestyle Kick - Surface</th>
<th>Change</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m.s⁻¹)</td>
<td>1.50</td>
<td>1.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total per cycle (Ns)</td>
<td>-6.95</td>
<td>-18.15</td>
<td>-11.20</td>
<td>-61.7%</td>
</tr>
<tr>
<td>Total per second (Ns)</td>
<td>-17.81</td>
<td>-46.53</td>
<td>-28.72</td>
<td>-61.7%</td>
</tr>
<tr>
<td>Body per second (Ns)</td>
<td>-21.35</td>
<td>-137.53</td>
<td>-116.18</td>
<td>-249.7%</td>
</tr>
<tr>
<td>Hips per second (Ns)</td>
<td>-1.21</td>
<td>-4.26</td>
<td>-3.05</td>
<td>-6.6%</td>
</tr>
<tr>
<td>Thighs per second (Ns)</td>
<td>1.75</td>
<td>33.13</td>
<td>31.38</td>
<td>67.4%</td>
</tr>
<tr>
<td>Knees per second (Ns)</td>
<td>-4.30</td>
<td>19.96</td>
<td>24.26</td>
<td>52.1%</td>
</tr>
<tr>
<td>Calves per second (Ns)</td>
<td>9.63</td>
<td>27.07</td>
<td>17.44</td>
<td>37.5%</td>
</tr>
<tr>
<td>Ankles per second (Ns)</td>
<td>13.64</td>
<td>3.73</td>
<td>-9.91</td>
<td>-21.3%</td>
</tr>
<tr>
<td>Feet per second (Ns)</td>
<td>-14.63</td>
<td>14.34</td>
<td>28.97</td>
<td>62.3%</td>
</tr>
</tbody>
</table>

Discussion

The differences between the fully submerged and near-surface passive models showed an overall difference in average drag of 11.3 N at 2.00 m.s⁻¹, or the equivalent of an 18.2% decrease when fully submerged. This correlates well with a study of experienced swimmers which found decreases in passive drag at 1.90 m.s⁻¹ and 2.20 m.s⁻¹, of 13.7% and 19.2%, respectively (Lyttle et al. 1998).

It is documented that the increased drag when decreasing depth near the surface, primarily is due to related increases in wave drag (Hertel 1966; Barltrop & Adams 1991). However, where the drag forces actually changed across the body segments remained unclear. Although the overall increase in passive drag force between the submerged and near-surface trials was 18%, there were significant differences between the body segments where those changes occurred. The head and arms generated the largest increases in drag, by contributing 44% (head) and 50% (arms) increase in the
near-surface overall drag. The overall section of the body above the waist resulted in a 121.7% increase in drag force but these increases were counteracted by the lower body components. The thighs, knees, calves and feet all recorded considerable reductions in drag; and the feet changed from an area of drag to a component propelling the body forward. The total change for the lower body components was a 103.5% drag reduction when compared with the overall submerged segment results.

The rationale for the differences around the body relate to the waves being formed at the water surface because the swimmer is closer to the air/water interface. This wave has a crest forward of the head region which is centred about the hands; and forms a trough just below the hips. This wave travels along with the swimmer with a length that is directly related to the swimmer’s velocity (using Linear Wave Theory; Barltrop & Adams 1991). Linear (or Airy) Wave Theory describes wave kinematics and dynamics sufficiently accurately for many purposes, with several 2nd order non-linear properties of surface gravity waves reported to be able to be estimated from its results (Goda 2000). In this wave that surrounds the swimmer, acceleration and velocity of the water varies greatly, and can influence the forces of the body components as they pass through those regions. The representative linear wave theory profile is depicted for reference in Figure 3 and Table 4. However, the specific passive glide and flutter kick wave profile from this study was predicted by the CFD model analysis (see Figure 4). Previous calculations by Keys (2010) found that the acceleration components of the wave properties were more important for human swimming than the velocity components.

Figure 3 & Table 4  Graphical representation of key area of a linear wave and table outlining the velocity and acceleration variations at critical points in a linear wave cycle (Barltrop & Adams 1991)

Figure 4  Illustrating the linear wave profile over the streamlined glide and freestyle kick simulations

The freestyle kick simulation also presented a similar wave profile but with a shortened overall wave length. The shorter wave length was a reflection of the reduced kicking simulation velocities when compared with the glide simulations (Figure 4). Results also reflected the linear wave force effects, with dramatic increases occurring at the surface for the upper body net drag forces when compared to being fully submerged; and these coincided with, for the most part, greater net propulsive forces about the lower body (Table 3). Again, this is proposed to be due to the upper body lying within the region of the wave front that exhibits a higher negative horizontal acceleration compared with the
lower body. The lower body tends to be positioned within the phases of the wave cycle with maximum positive horizontal accelerations, as outlined within the Linear Wave Theory.

Comparing the force output data from the foot and calf areas over time, revealed a similar offset between the two simulation outputs for ~60% of the time. The near-surface simulation displayed increased net propulsive force values in both cases. However, in periods where the feet and calves lose contact with the water surface in the surface model, this offset changed; with the fully submerged case increasing the propulsion rate faster and producing more propulsion, than the surface model. This represented a major loss in swimming propulsion because the acceleration phase of the foot begins here; and, also, is where the maximum point of horizontal acceleration of the water within the wave takes place. Based on an average drag force of 40N at 1.5m/s, this would equate to a speed increase of ~5% by just preventing both the left and right foot from breaking the water surface at any time, provided this technique change does not lead to losses elsewhere.

**Conclusion**

The inability of previous empirical measurement techniques to differentiate the drag forces into separate forces for each body part, has led to drawing only broad, and sometimes questionable, conclusions. The mathematical approaches and, more recently, the CFD simulations, have provided greater insight into both the steady and unsteady forces acting on a body, and the variation of those forces throughout a swimming cycle. Only with an understanding of where these forces are acting, can swimmers, sport scientists and coaches make informed technique modifications to maximise a swimmer’s potential and minimise injuries. This analysis increases our understanding of net forces produced across the body during gliding and the freestyle kick, at different depths. It also found that forces on various body components can undergo large changes between full submersion and near the surface.

**References**

Effect of jumping timing on resultant height for lift in synchronised swimming

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Keywords: synchronised swimming, lift, jumping height, simulation, SWUM

Abstract
The objective of this study was to clarify the effect of jumping timing on resultant height for lift in synchronised swimming by means of the computer simulation. The lift by four swimmers, which consists of one upper, one middle and two lower swimmers in the formation was analyzed in the present study. The body geometries and joint motions of the swimmers were put into the simulation model. The equations of motion for the translational movements of the four swimmers were solved computationally, and the jumping height of the upper swimmer was obtained. By virtually changing the timing of motion among swimmers in the simulation, a parameter study about the effect of jumping timing on resultant height was carried out. From the parameter study, following findings were obtained: It is important to synchronise the jumping motions of the upper and middle swimmers. Both the earlier and later jumps by the upper swimmer result lower jumping height. The gain due to the synchronisation is 0.5-0.7 m. The synchronised motion causes significant increase in the hip joint torque of the upper swimmer. This increase, however, can be reduced by taking an appropriate position during jumping motion.

Introduction
In synchronised swimming, both the advancement of techniques and the artistic impression are required in order to obtain a high evaluation. Among various routines in synchronised swimming, ‘lift’ is a move in which one or two swimmers are elevated by the other swimmers and finally launched in the air. Since the jumping height is required for evaluation, it is important for the swimmers and coaches of synchronised swimming to clarify theoretically how the higher jumping height is achieved. Some technical elements of the synchronised swimming, such as the sculling (Ito 2007) and the eggbeater kick (Homma & Homma 2006), have been studied from the mechanical viewpoint to date. However, no theoretical approach which can handle the mechanics of a whole move, such as the lift, has been conducted. If such a theoretical method is established, it will be useful to investigate various mechanical problems of synchronised swimming. Therefore, Nakashima et al. (2013) developed the simulation method for synchronised swimming which can simulate the whole move. The simulation method was developed by extending the swimming human simulation model ‘SWUM’ (Nakashima et al. 2007). The validity of the developed simulation method was confirmed since the simulated time variations in the vertical displacement of the swimmers were consistent with the experimental ones (Nakashima et al. 2013). The same simulation method was used in the present study as well. The objective of this study was to clarify the effect of jumping timing on resultant height for lift by four swimmers in synchronised swimming by means of the computer simulation. Although it was partly
discussed (Nakashima et al. 2013), the detailed effect and the required joint torque are fully discussed in the present study.

**Methods**

The swimming human simulation model ‘SWUM’ was utilised for the simulation of the present study. SWUM was designed to solve the six degrees-of-freedom absolute movement of the whole swimmer’s body as a single rigid body by time integration using the inputs of the swimmer’s body geometry and relative joint motion. Therefore, the swimming speed, roll, pitch and yaw motions, propulsive efficiency, joint torques and so on, are computed as the output data. The swimmer’s body is represented by a series of 21 rigid body segments. Each body segment is represented by a truncated elliptic cone. The unsteady fluid force and gravitational force are taken into account as external forces acting on the whole body. The unsteady fluid force is assumed to be the sum of the inertial force due to the added mass of the fluid, normal and tangential drag forces and buoyancy. These components are assumed to be computable, without solving the flow, from the local position (for buoyancy of not-fully submerged body), velocity, acceleration, direction, angular velocity, and angular acceleration for each part of the human body at each time step. The coefficients in this fluid force model were identified in the reference (Nakashima et al. 2007) using the results of an experiment with a limb model and measurements of the drag acting on swimmers taking a glide position. The recent progress related to SWUM including its validation was reviewed in the reference (Nakashima 2010). Some of the analysis data and animation movies are open to the public at the SWUM website (http://www.swum.org/).

The simulation model of synchronised swimming was constructed by extending SWUM. The function of the ‘Multi Agent/Object Simulation’ (Nakashima et al. 2010) was employed for this purpose. Using this function, the swimming motions of the four swimmers were simultaneously calculated in the time-marching computation. The schematic figure of the simulation model is shown in Figure 1. The four swimmers perform the swimming motion independently. The connections among the swimmers, whose points are represented by the red circles in the figure, are realised by the virtual springs and dampers. The forces due to the springs and dampers, which are denoted by F in the figure, act on the swimmers as external forces. The rigid connection between two swimmers can be reproduced if the springs are stiff enough, since the relative displacement at the connecting point becomes sufficiently small. The virtual dampers were added in order to stabilise the calculation. The values of spring stiffness and damping coefficients in the simulation were determined by means of a parameter study in which they were increased until the relative displacements among the swimmers became sufficiently small.
In the following simulations of the lift, the two feet of the upper swimmer are connected to the shoulder of the middle swimmer, as shown as red circles in Figure 1. The two feet of the middle swimmer were connected to the hands of the lower swimmers. In addition, the connecting forces were assumed to act only when the vertical components of the forces were in a compressing direction, that is, when the swimmers pushed each other. When the components are in a stretching direction, the forces were compulsorily set as zero. This implementation enabled the automatic and natural launch (release) of the upper swimmer, that is, the timing of release was not determined in advance.

In the previous study (Nakashima et al. 2013), four female swimmers were recruited from the Japan National Team of synchronised swimming. The body geometries and joint motions of the swimmers were experimentally measured, and those were put into the simulation of the present study. The temporal change in the vertical displacement of the center of mass for the upper swimmer was obtained from the simulation. The maximum vertical displacement was taken as the ‘jumping height’.

It should be noted that only the translational movements of the swimmers were solved by the time-marching method. The rotating movements (angles in the three-dimensional space) were given as input, the same as with the joint angles. This was because the translational movements, such as jumping height, were most important in the present study, and because the problem became too complicated if the rotating movements were taken into account.

**Results and discussion**

It was suggested that the jumping timing of the upper swimmer significantly affected the resultant jumping height (Nakashima et al. 2013). Therefore a parameter study, in which the jumping timing of the upper swimmer was virtually changed, was carried out. The relationship between the changed amount of timing and the jumping height is shown in Figure 2. From this figure, it was found that the jumping height became maximum when the upper swimmer jumped 0.07 s earlier. The animation images for the 0.07 s earlier timing are shown in Figure 3, and the snapshots at \( t = 1.95 \) s for two timings of the original and 0.07 s earlier are shown in Figure 4. From Figure 4, it was found that the jumping motions of the upper and middle swimmers were almost synchronised when the upper swimmer jumped earlier, while the jump of the upper swimmer was apparently later than the middle swimmer in the case of original timing. So it can be concluded that it is important to synchronise the jumping motions of the upper and middle swimmers. From Figure 2, it was found that both the earlier and later jumps by the upper swimmer result lower jumping height, and that the gain due to the synchronisation was 0.5-0.7 m.

![Figure 2](image)  
**Figure 2** Relationship between the jumping timing between resultant height
In order to perform the appropriate jumping motion, large joint torque at the lower limbs may be necessary. The simulated average joint torques at the hip and knee (for one limb) during hip extension for the jump as well as the jumping height are shown in Table 1. For the (0.07 s) earlier timing, the joint torque at the hip became more than twice of that for the original timing. This large value suggests that the (improved) earlier jump is not feasible for the actual swimmers. However, the hip joint torque can be reduced by taking an appropriate position for the upper swimmer. This is schematically explained in Figure 5. As shown in Figure 5(a), the moment arm of the moment acting on the upper swimmer about the hip joint is basically the horizontal distance between the point of application of the force from the middle swimmer (foot) and the hip joint, since the direction of the reaction force from the middle swimmer is basically upward. This moment arm can be reduced by bringing the hip forward as shown in Figure 5(b). In this case, the joint torque opposing the external moment can be smaller as well. Therefore, a simulation, in which the position of the upper swimmer was changed, was carried out. In this simulation, the upper swimmer was rotated for 25 degrees in the counterclockwise direction as a whole, as shown in Figure 5(b). The result is shown in Table 1 (earlier & modified position). It was found that the hip joint torque became half (157 Nm) of the simulation of the unmodified position (333 Nm). Although the jumping height became lower (1.55 m), it was still 0.27 m higher than the height of the original motion.

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>Earlier</th>
<th>Earlier &amp; modified position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip joint torque (extension) [Nm]</td>
<td>140</td>
<td>333</td>
<td>157</td>
</tr>
<tr>
<td>Knee joint torque (extension) [Nm]</td>
<td>30</td>
<td>-50</td>
<td>-88</td>
</tr>
<tr>
<td>Jumping height [m]</td>
<td>1.28</td>
<td>1.97</td>
<td>1.55</td>
</tr>
</tbody>
</table>
Conclusions
The obtained findings in the present study are as follows:

- It is important to synchronise the jumping motions of the upper and middle swimmers. Both the earlier and later jumps by the upper swimmer result lower jumping height.

- The gain due to the synchronisation is 0.5–0.7 m.

- The synchronised motion causes significant increase in the hip joint torque of the upper swimmer. This increase, however, can be reduced by taking an appropriate position during jumping motion.

References


Unsteady hydrodynamic forces acting on a robotic arm and its flow field during the crawl

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Introduction

The importance of unsteady phenomena in human swimming has been emphasized in previous studies (Sanders 1999; Toussaint et al. 2002), hence we know that quasi-steady hydrodynamic theory is insufficient to describe the mechanisms by which humans propel themselves through water. To address such problems, computational fluid dynamics (CFD), including the effects of unsteady fluid flow, has been making a major contribution to understanding hydrodynamic phenomenon when the swimmer was moving actively either on the surface or underwater (Von Loebbecke et al. 2009; Dabnichki 2011). Particle image velocimetry (PIV) has also proven to be a powerful tool for measuring the actual flow fields around human swimmers. Based on PIV measurements, Matsuuchi et al. (2009) have reported that a pair of counter-rotating vortices might play an important role in generating unsteady fluid forces, and Hochstein and Blickhan (2011) have found that vortices generated in the region of strongly flexing joints are suitable to enhance propulsion; this process is known as vortex recapturing. Combining the results from CFD and PIV should help in visually and theoretically understanding complicated hydrodynamic mechanisms. However, actual experiment data, such as for forces and pressures, are also valuable for verifying CFD results and interpreting PIV images. Therefore, in a previous study, we conducted experiments in which we directly measured hydrodynamic forces, pressure distributions, and flow fields around a hand attached to a robotic arm (Takagi et al. 2013). In that work, simple 2D hand motions were the subject for study; nevertheless, a significant unsteady hydrodynamic phenomenon was observed that reveals the behavior of certain kinds of vortices play an essential role in generating substantial unsteady hydrodynamic forces. In this study, we used a robotic arm and PIV to clarify the mechanisms by which unsteady forces are generated during 3D crawl-stroke-motions. By analyzing the 3D motions, it is expected that actual propelling mechanisms can be elucidated and the findings will contribute to an improvement of swimmers’ technique.

Method

Robotic arm and hand models

A robotic arm that consisted of a trunk, shoulder, upper arm, forearm, and hand (Takagi et al. 2013) was used. The robotic arm had five degrees of freedom (DOF), which were driven by three motors housed in the trunk and two motors housed in the upper arm and forearm.

Two hand models were fabricated from a silicon-based material (Takagi et al. 2013). One hand (Hand 1) was used to measure hydrodynamic forces via flow visualisation, and another (Hand 2) was used to measure pressure distributions during stroking motions. Eight pressure sensors were embedded in Hand 2 to measure the pressure distribution on its surface (Fig.1).
 Definitions of the coordinate system and technical terms

The origin of the global coordinate system was set at the center of the shoulder joint, as shown in Fig. 1. The x-direction was parallel to the main flow, the z-direction was upward and perpendicular to the main flow, and the y-direction was normal to the x- and z-directions. In this study, the following successive phases during one underwater stroke were defined by reference to Maglischo (2003).

Downsweep is the phase during which the hand enters the water and moves outward/downward until the hand reaches the local maximal value of the y-coordinate. Insweep is the phase during which the hand’s moving vector \( \mathbf{U}_h \) changes direction to the centerline of the body until the hand reaches the local maximal value of the z-coordinate. Upsweep is the phase during which \( \mathbf{U}_h \) changes direction to outward/upward until the hand leaves the water.

Particle image velocimetry (PIV)

Two-component PIV was used to visualise flow around Hand 1. An Nd-YAG laser (Solo PIV 120 XT; New Wave Research Inc., USA) was used and a wide range of hand motions (0.5 m × 0.5 m) were covered. Nylon particles of 50 μm diameter (DAIAMID 2157; Daicel-Evonik Ltd., Japan) were used as tracers. The particle displacements \( \Delta x, \Delta y \) that occur during a short time \( \Delta t \) determine velocities by

\[
\begin{align*}
 u &= \frac{\Delta x}{\Delta t}, \\
 v &= \frac{\Delta y}{\Delta t}
\end{align*}
\]

where \((u, v)\) are the components of particle velocities in the x- and y-directions, respectively. In the present experiment, \( \Delta t \) was set to 1 ms.

The vorticity was obtained to study the generation of forces that can be attributed to vortex generation and shedding. Vorticity is the measure of the rotational magnitude of a small fluid element or that of a vortex (Matsuuchi et al. 2009). The component normal \((\zeta)\) to the measured \((x-y)\) plane is defined as

\[
\zeta = \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}
\]
Computer-generated maps of vorticity and velocity around the hand were obtained every 67 ms by a cross-correlation-based two-component PIV algorithm (Sakakibara et al. 2004).

**Reproduction of human swimming motion**

An international-level female swimmer was used as a model, kinematic data of the motion of her right upper limb during the stroke were captured, and the data were loaded into the swimming human simulation software Swumsuit (Nakashima 2007). Through Swumsuit, the robotic arm is computer controllable in the five independent DOFs to reproduce the swimmer’s motion, as much as possible. The motion was highly reliable (the error between the measured angle and the commanded angle was within 5%) and accurate data for forces were obtained (Nakashima & Takahashi 2012). Since the reproduced hand path looked like an ‘S’, we call it Stroke S. We also modified the motion of Stroke S to make its trajectory more straightforward during Insweep and to reduce fluctuations in y-coordinate values; we call this Stroke I. The ranges of motion and durations from when the hand entered the water until it left the water were the same for both strokes S and I.

**Data acquisition of forces, flow visualisation, and pressure distributions**

The robotic arm was fixed above the measuring section with a 2D load cell (LSM-B-SA1; Kyowa Electronic Instruments Co., Japan), as shown in Fig. 1. The constant flow velocity ($U_c$) was set to one of three different values: 0.36, 0.46, or 0.56 m/s. The maximum Reynolds numbers for strokes S and I were $1.48 \times 10^5$ and $1.31 \times 10^5$, respectively.

3D hand positions were calculated from the data obtained from position sensors. Data for positions and forces were sampled at 200 Hz and stored on the PC. By simultaneously recording these data and the trigger signal from the PIV system, all data related to hand displacement, hydrodynamic forces, and flow visualisation around it were synchronised. To assess hydrodynamic forces acting only on the hand (Hand 1), the force acting on the robotic arm without the hand was measured before experimentation and then subtracted the force without the hand from that with the hand. After the hydrodynamic force measurements and flow visualisation experiments, pressure distributions were measured by using Hand 2. This enables us to discuss relationships between pressure distributions and changes in the flow field. All conditions were similar to the first experiment; for example, the pressure data were sampled at 200 Hz.

**Results**

The largest thrust force was observed at $U_c = 0.36$ m/s, and in both stroke patterns, the thrust force peaks decreased with an increase in $U_c$. Thrust forces in Stroke S show bimodal peaks; the larger peaks occur in the latter part of the motion when the hand was switching from Insweep to Upsweep. In contrast, Stroke I shows single peaks in thrust forces near the middle part of the motion. The highest peaks in strokes S and I were 17.5 N and 27.5 N, respectively. Both stroke patterns exhibited negative thrust forces in the last parts of the motion, which correspond to Upsweep phases.

For Stroke S, when thrust forces reached maximum values, the hand changed from Insweep to Upsweep, a clockwise vortex was shedding from the thumb side due to the change in the hand’s direction of movement. This shedding vortex caused a new fluid circulation around the hand occurred (See Fig.2). At that time, a decrease in pressure over the dorsal side of hand was observed.

For Stroke I, when the peak thrust force occurred, $V$ reached its maximum, a Kármán vortex street was generated from the thumb or finger side. At that time, the pressure on the palm side had large positive values, while on the dorsal side the pressures were negative though not large absolute values.
**Discussion**

In this study, hydrodynamic forces, pressure distributions, and flow visualisations were measured during the crawl stroke using a robotic arm. We adopted two types of crawl strokes $S$ and $I$, but we did not focus most of our attention on comparison. Although the peak thrust force in Stroke $I$ was larger than that in Stroke $S$, the inferior-to-superior relationship would change depending on conditions; therefore, we focused on differences in the mechanisms for generating hydrodynamic forces acting on the hand.

To provide an easy-to-understand explanation for the mechanism of generating hydrodynamic forces during the crawl stroke, conceptual diagrams were constructed and are shown in Fig. 2. In the case of Stroke $S$ (upper drawing), a vortex was shed from the hand when it changes from Insweep to Upsweep. Before shedding the vortex, the thumb side was the leading edge and the direction of the bound vortex was clockwise; after shedding, the direction of the bound vortex becomes counterclockwise, in accordance with Kelvin’s circulation theorem. By adding this circulation to the moving velocity, the surface velocity increased, the surface pressure decreased, and a lift force was produced. At that time, the leading edge was the little-finger-side, and the resultant flow ($V$) was inward from the little-finger-side, as shown in the figure. Since the lift force acts perpendicular to $V$, the lift force must contribute to an increase in the thrust force. This phenomenon is known as the unsteady mechanism of force generation that insects apply for flying (Dickinson 1996).

In the case of Stroke $I$ (lower drawing in Fig. 2), when the hand moved in a linear manner with a large angle of attack, a Kármán vortex street was generated, and clockwise or counterclockwise vortices were alternately shedding from it. At that time, the pressure on the palm side was large and positive, and the pressure difference between the palm and dorsal sides increased, producing a drag force. This drag force must contribute to an increase in the thrust force.

*Figure 2* Conceptual diagrams of hydrodynamic forces acting on the hand during Stroke $S$ (upper panel) and Stroke $I$ (lower panel)
We have been able to unravel parts of the hydrodynamic mechanisms during the crawl stroke, but we also recognise some limitations. For example, the resultant flow vectors relative to the hand (V) achieved by the robotic arm did not reach 1.7 m/s at the maximum; in fact, they were approximately half of those in actual swimming motions (Maglischo 2003). In addition, the robotic arm had no degree-of-freedom at the wrist joint, thus palmar flexion and dorsal flexion of the wrist could not be reproduced. These differences and defects were due to limitations on the output power and driving mechanisms of the robotic arm. Only 2D flow-field images during crawl-stroke-motions were obtained in this study. Since hand movements are 3D, it would be better to obtain 3D vortices and velocity distributions; this has not yet been done due to limitations on the number of CCD cameras and on the performance of the software.

References
5 Medicine

Ventilation dynamics during race pace swimming in elite competitive swimmers

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1Unit for Sports and Exercise Medicine, Institute of Clinical Medicine, University of Helsinki, 2Foundation for Sports and Exercise Medicine, Clinic for Sports and Exercise Medicine, 3Finnish Society of Sport Sciences

Abstract

Introduction: Respiratory symptoms are common among competitive swimmers. The most respiratory symptoms have been reported during very hard, race pace swimming. It has been suggested that extreme strain with high pulmonary load would have an effect on development of asthmatic symptoms among athletes. The aim of the study was to examine pulmonary ventilation during very hard intensity, race pace swimming in elite competitive swimmers.

Methods: Fourteen healthy elite swimmers, 7 females and 7 males, 18 years old, with training history of 9 years on the average were studied. Maximal ventilation (VEmax) was measured breath-by-breath during race-pace swimming. Maximal voluntary ventilation (MVV) was measured on land (L) and in water (W) in prone swimming body position. MVV was also estimated (cMVV) by calculating 35-FEV1 on L and W. Measurements were performed by portable Cosmed K4b2 analyzer. Snorkel build for swimming testing was attached to the breathing valve.

Results: During the swim, VEmax was 106 (4) l-min⁻¹ in females and 136 (14) l-min⁻¹ in males. Breathing reserve (Br) was 27% in females and 25% in males when LcMVV. However with WcMVV, Br decreased to 24% in females and 20% in males in comparison to LcMVV. When pooled data on LMVV, WMVV, LcMVV and WcMVV were examined, WMVV correlated the most with VEmax. During the race pace swim VEmax reached 76% in females and 80% in males of the calculated maximal voluntary ventilation in water.

Discussion: Results indicate that during the race pace intensity swimming, the extremely high load on the pulmonary function induces asthmatic respiratory symptoms in elite competitive swimmers. The observation that the VEmax was 76-80% of the WcMVV, was higher than the target ventilations used to detect respiratory symptoms in physical exercise at 60% of LcMVV. Therefore, we suggest that the special effects of swimming and water environment on pulmonary function should be taken into account when analyzing respiratory hazards in elite swimmers.

Introduction

Respiratory symptoms are common medical problems among elite endurance athletes, also in swimmers1,2. Even though, relieving of respiratory symptoms has been observed in connection to swimming training in asthmatics3,4,5. Reported respiratory symptoms in competitive swimmers (wheezeing, coughing, shortness of breath and mucous production) during swimming at five different exercise intensities (easy, moderate, hard, very hard and maximal sprinting) have been studied in previous studies6,7. Competitive swimmers reported respiratory symptoms the most during very hard intensity race pace swimming8.

Special adaptation of competitive swimming training for ventilatory function have been observed in elite swimmers8,9. Higher than predicted volumes and capacities have been shown in competitive swimmers. Previous studies suggest that large lung volumes and capacities may be caused by
intensive and extensive swimming training at young age\textsuperscript{10,9}, repeated rapid inhalation near total lung capacity (TLC), negative pressure during inhalation, prolonged exhalation to water and prone body position during swimming. Face immersion\textsuperscript{11} has also special effect on breathing in comparison to normal breathing on land.

Respiratory symptoms during swimming differ from symptoms in sports on land because of the different ventilation dynamics. Ventilation dynamics in physical exercise in water is different mainly due to hydrostatic pressure on chest wall. The air pressure in lungs near the water surface in swimming body position is approximately 89 kPa with the depth of water approximately 20 cm H\textsubscript{2}O. The hydrostatic pressure also have major effects on blood circulation and redistribution of blood volumes in the body\textsuperscript{12}. In addition horizontal body position during swimming optimise lung perfusion and induces the best possible lung diffusion capacity\textsuperscript{13}. Breathing pattern is restricted during swimming due to the arm stroking rhythm.

Aim of this study was to investigate the ventilation function in healthy elite swimmers during swimming at race pace, which is the major trigger for respiratory symptoms.

**Methods**

Fourteen swimmers, 7 females and 7 males, were studied. Selection criteria for the subjects was that they should be healthy without physician diagnosed asthma, allergies or reported respiratory symptoms during swimming and to have sufficient training background and performance level. The training history for competitive swimming was 9 years on the average for all studied swimmers and they all had performed in the Finnish national championships as finalists (among the best 8) in their major discipline.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Demographics of 14 healthy elite competitive swimmers, mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N=14</td>
<td>Age y (years)</td>
</tr>
<tr>
<td>Females 7</td>
<td>18 (2)</td>
</tr>
<tr>
<td>Males 7</td>
<td>18 (2)</td>
</tr>
</tbody>
</table>

The study procedure:

1. **Flow-volume spirometry and MVV measurements on land (LMVV and LcMVV).**
2. **Flow-volume spirometry and MVV measurements in water (WMVV and WcMVV).** Swimmer was floating in prone swimming body position, holding on the side of pool deck keeping face immersed. Pull buoy was kept between tights to avoid foot from sinking.
3. **Maximal ventilation (VEmax), breathing frequency (Fb), and tidal volume VT measurement during very hard intensity race pace swimming 100 meters freestyle.** Picture 1

Spirometry and ventilation measurements were performed with portable Cosmed K4b\textsuperscript{2} gas analyzer. Forced vital capacity (FVC), forced expiratory volume for 1 second (FEV\textsubscript{1}), the percentage of FVC and FEV\textsubscript{1} (FEV\%)

and maximal voluntary ventilation (MVV) were studied with flow-volume spirometry and MVV measurements on land and in water before very hard intensity race pace swimming.

Spirometry testing was performed according to ATS/ERS guidelines for spirometry testing \textsuperscript{14}. Results of FVC, FEV\textsubscript{1}, FEV\% on land were compared to the age, size and sex matched predicted values by the spirometric counting equations for Finnish population by Viljanen \textsuperscript{5}.

To obtain VEmax during very hard intensity race pace swimming the breath-by-breath method of K4b\textsuperscript{2} gas analyzer was used. Calculated maximal voluntary ventilation (cMVV) was calculated with the
equation of FEV$_1$-35$^{15}$ and both measurements FEV$_1$ on land and in water were used. Both were also used when the breathing reserve (Br) was calculated for the very hard intensity race pace swimming.

Special snorkel was used for performing the measurements both on land and water$^{16}$. Snorkel was attached to the breathing valve. The testing system has been validated by Keskinen et al.$^{17}$ Dead space formed by the equipments was 710ml; expiration tube 480ml, mouthpiece 40ml and connecting piece 190ml. Picture 3. Valve was connected to computer with a cable. Before each test Cosmed K4b$^2$ analyzer was calibrated. Special delay calibration was performed with the flow calibration. Measuring equipments were moved along with the swimmer from the pool deck (Picture 1). The ethics committee of University of Jyväskylä approved the study procedure. Picture 1 Ventilation measurements during race pace swimming

Picture 2 Testing equipments: Snorkel and valve connected to the Cosmed K4b$^2$ analyzer.

**Results**

All of the swimmers had a normal spirometry finding. Significant gender difference was found in FEV$_1$ in percent of predicted (Table 2).

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Flow-volume spirometry in elite swimmers, presented as percent % of predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Female swimmers</td>
</tr>
<tr>
<td>FEV$_1$ % of predicted</td>
<td>112 (6)</td>
</tr>
<tr>
<td>FVC % of predicted</td>
<td>112 (9)</td>
</tr>
<tr>
<td>FEV% % of predicted</td>
<td>99 (8)</td>
</tr>
</tbody>
</table>

*Significant difference

No significant gender difference in breathing reserve during very hard race pace swimming (Table 3) was found either.
Table 3  Maximal ventilation (VEmax), tidal volume (VT) and breathing frequency (RF) during race pace intensity swimming and comparison to maximum voluntary ventilation (MVV)

<table>
<thead>
<tr>
<th></th>
<th>Female swimmers</th>
<th>Male swimmers</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEmax (l/min-1)</td>
<td>106 (4)</td>
<td>136 (14)</td>
</tr>
<tr>
<td>VT (l)</td>
<td>2.5 (0.4)</td>
<td>3.6 (0.3)</td>
</tr>
<tr>
<td>RF (breaths-min-1)</td>
<td>56 (12)</td>
<td>54 (8)</td>
</tr>
<tr>
<td>MVV land (l/min^-1)</td>
<td>148 (20)</td>
<td>189 (22)</td>
</tr>
<tr>
<td>MVV water (l/min^-1)</td>
<td>138 (16)</td>
<td>176 (23)</td>
</tr>
<tr>
<td>cMVV 35- FEV1 land</td>
<td>145 (17)</td>
<td>181 (17)</td>
</tr>
<tr>
<td>cMVV 35- FEV1 water</td>
<td>136 (18)</td>
<td>167 (13)</td>
</tr>
<tr>
<td>VEmax % of cMVV land</td>
<td>72 (7)</td>
<td>75 (7)</td>
</tr>
<tr>
<td>VEmax % of cMVV water</td>
<td>76 (8)</td>
<td>80 (7)</td>
</tr>
</tbody>
</table>

**Figure 1**  Linear regression of VEmax during swimming and MVV on land p<0.01.

**Figure 2**  Linear regression of VEmax during swimming and MVV in water p<0.001.

**Discussion**

In this study during very hard race pace intensity swimming the healthy elite swimmers reached 72% of LcMVV (35-FEV1 on land) in females and 75% of LcMVV in males. When observed with WcMVV (35-FEV1 in water) the female swimmers reached 76% and male swimmers 80% of the WcMVV (Table 4). The intensity the studied swimmers swam was the very same intensity where the experienced swimmers report respiratory symptoms the most in previous studies. The intensity zone IV is harder than the speed maximal VO2 max consumption intensity with maximising muscle lactic acid consumption19.

Swimming intensity has had in previous studies an important role in reported respiratory symptoms6. Hard and very hard (race pace) intensity swimming were significant risk factors for reported respiratory symptoms in competitive swimmers6.

Typically respiratory symptoms with suspect of exercise induced asthma are studied with exercise challenge test by the exercise medicine specialised physicians. Exercise challenge is typically performed on treadmill or bicycle ergometer for 6-8 minutes with target heart rate of 80-90% of
predicted maximal heart rate (hr) = 220-age and ventilation should reach 40-60% of the predicted MVV as estimated by FEV₁:35. It is preferable that the target ventilation would be maintained for 4 minutes at least during challenge test.

In this study the swimmers performed at the very hard intensity. Their ventilation reached close the target ventilation of 60% from calculated MVV (35-FEV₁) which is required for exercise challenge on land (used typically for exercise challenge) when cMVV was calculated of the FEV₁ measured in water environment.

The results show that during the very hard race pace swimming intensity the swimmers reached closely the same ventilation level as targeted intensity that is used in exercise challenge testing for exercise induced asthma.

During swimming exhalation is performed into water. While the resistance of water causes additional pressure on the lungs it may ease the exhalation in persons suffering asthma symptoms. This resistance was not present in our measurements and that is something that may also have important role on the reported respiratory symptoms in competitive swimmers.

In competitive swimmers, out of the measured LMVV, LcMVV, WMVV and WcMVV, the WMVV correlated the most with the measured VEmax during swimming. Therefore the target ventilation for swimming exercise challenge may be reasonable to be calculated from the MVV and FEV₁ measured in water in swimming body position.

Swimming, cycling and EVH challenges on the decrease of FEV₁ were studied by Castricum et al (2008). They had 8 minute challenge in swimming, cycling and EVH. None except one of the studied swimmers had a finding with swimming challenge test. However they all had a finding in EVH. Ventilation was not recorded. In conclusion of the results of this study and Castricum et al. it may be suggested, that for elite swimmers (with suspect of exercise induced asthma) to provoke asthmatic reaction in swimming challenge test with FEV₁ fall finding, it may require higher intensity level.

Swimming has been shown to be low asthmogenic and induce less symptoms on same intensity level than running or cycling. Also water environment cause special effects on ventilation compared to exercise on land. Therefore in theory the finding of present study suggest that higher intensity challenge test with even shorter duration than used at exercise challenge on land, may be useful when studying symptoms and ventilatory function connected to swimming exertion in elite competitive swimmers. That way the challenge would be performed on the intensity where the symptoms are known to be reported the most. That may offer more precise and sport-specific information for elite athletes and coaches, in order to provoke symptoms during swimming exercise challenge test at specifically adjusted triggering intensity. It may further help in treating symptoms and it is useful to know exactly how the ventilation is functioning during swimming workouts of the elite swimmers aiming for the international top. It is important to notice that these goals are different, than the ones needed to show the findings for the diagnosis of disease and prescription for the medication needed.

Suitable asthma medication together with the knowledge of training specific information about the optimal symptom free intensity training is required to secure optimal training conditions for elite swimmers. For physicians this specified information of ventilation function typical for respiratory symptoms in elite competitive swimmers is useful for recognising the differences between exercise ventilation on water and land in exercise challenge test and for estimating the optimal target ventilation for exercise challenges when testing elite competitive swimmers.

References

Evaluation of master swimmers health: the case of French National Championships

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1Research Team in Sport and Society, Lille 2 University

Keywords: physical activity, age, competition, strategy

Regular physical activity has long been considered as a main condition for a healthy life style. This idea was strengthened with observational studies in the general population (Brown et al. 2004) and in patients (Abell et al. 2005) suggesting that physical activity is associated with both physical benefits
and all health-related quality of life dimensions. In that way, several program of promotion of physical activity are performed over the world. The consensual recommendations state that all adults should accumulate a minima of physical activity of moderate or greater intensity, preferably on every day of the week (Cabezas et al. 2007)

Among physical activity exercises, swimming is often recommended to increase physical activity and gain health benefits by various authoritative groups and researchers. Practicing swimming has showed multiple positive effects on health concerning the prevention and treatment of cardiovascular disease (European Society 2003), improving cardiorespiratory fitness values (Sieverdes et al. 2012), and decreasing body mass index (Cox et al. 2010; Sacher et al. 2010), or blood pressure (Tanaka et al. 1997). Considered as an aerobic exercise like jogging, walking or cycling, emotional states benefits have also been reported in healthy people and clinical population practicing swimming such as anxiety depression, mood or self esteem (Guszkowska M. 2004). Despite studies showing swimming may sometimes have detrimental effects on the respiratory system due to chloramine context (Bougault et al. 2009), injuries involving shoulder or spine (Gaunt & Mafulli 2012) or in blood pressure increase (Cox et al. 2005), swimming is recognised over the world as an effective healthy promotion measure.

To our knowledge, majority of studies aiming to assess the health benefits of swimming focused on specific parameters corresponding either to medical or psychological field. Moreover, experimental designs are often conducted in short period (from 6 weeks to one year) reducing the long term impact of this practice over the multi health parameters. Yet, according to World Health Organization (WHO) the health concept has to be defined as ‘a complete state of mental, physical and social well being’ and considered as ‘a resource for every day life’ (WHO report, 1986) suggesting a multi-physiological psychological and social parameters analyses for studying health benefits by swimming.

In that way, ‘competitive master swimmers’ appeared to be interesting subjects for studying health benefits by swimming because they spend more time training in comparison with the average sedentary aging person and allowed a long term effect of swimming practice. This population could be defined as adults swimmers aged from 25 to over 90 years old, involved in a regular training process, and committed in several competitions during a year. Dionigi (2006) suggested that older people who compete in sport are ‘resisting the dominant negative stereotypes associated with aging and feeling empowered to live a fulfilled and healthy life’.

Thus the aim of this study was to analyze physiological and psychological indices of health in master swimmers participating in French championships in conjunction with comparative general populations in order to gain better understanding of the links between swimming physical activity, competitive practice, and benefits in health according to gender and ages.

**Methods**

The research hypotheses were examined by comparing several health parameters currently used in the literature (body mass index, peak expiratory flow, mental and psychological indicators) to general values recorded in standard population in France or Europe.

**Participants**

490 master swimmers (227 females and 263 males) were recruited during the French master swimming championships in which 1554 swimmers were present. Participants were aged from 25 to 95 years old (45.9±13.2 years and 45.6±12.9 years for women and men respectively). During the 5 days of the competition, surveys concerning mental health were administered to volunteered participants. At their convenience, they were invited to pass to the ‘measures room’ where height, weight, and peak expiratory flow performances were measured. Before any data collection, ethics consent was granted through the French National Ethics Committee.
Data collection

Physical health indicators

Body Mass Index (BMI, kg.m$^2$) was used to measure overweight and obesity. Weight and height were directly measured because self reported data may provide an under-estimated of true BMI (Gorber et al. 2007). Overweight and obesity were defined according to the WHO cut off (1997) as, respectively, 25 ≤ BMI < 30 kg/m$^2$ and BMI ≥30 kg/m$^2$. Lung function was evaluated by peak expiratory flow (PEF, l.min$^{-1}$) in all subjects who did not smoke or use inhalers 1 hour prior to the test. A single observer, who explained the purpose of the study and then demonstrated the correct manner of performing the test, supervised all the tests. Subjects were observed while they made several trial attempts in order to detect faults in technique. Once they were able to perform the test correctly they were exhorted to make a maximum effort and the highest value achieved in three tests in the standing position was recorded to the nearest.

Mental and social health indicators

Mental and social health was evaluated via the SF 36 (Jenkinson et al. 1993) survey. Seven of the current 8 multi-item variables were measured: social functioning, role limitations due to physical problems, role limitations due to emotional problems, mental health, energy and vitality, pain, and general perception of health. Each item was scored according to a rate of 100. The higher the score, the better the health parameter.

Statistics

Data are shown as mean ± SD. Normal Gaussian distribution and homoscedasticity of the data were verified by the Shapiro-Wilk’s and Levenne tests, respectively. When these conditions were respected, parametric tests were used (Student t test, ANOVA). Otherwise, no parametric tests were used (U Mann & Whitney, Friedman ANOVA). Concerning comparison of rate of population, Chi 2 test was used to differentiate master swimmer to standard population. According to references used for comparison, age classes have been modified to allow statistical comparison. When gender effect was used in the references, master swimmers data have been classified according to gender.

BMI (kg.m$^2$) values were compared with results of study of Charles et al. (2008). SF 36 scores were compared with values resulted from the study of Jenkinson et al. (1993). Single sample t test was used to compare the sample mean values with the reference value. PEF scores were compared with predictive values resulted from the study of Nunn and Greg (1989). Measured values were compared with predictive values by a two way ANOVA (age-gender).

For all tests used, the level of confidence was set at 0.05. Bonferroni correction was used to avoid type 1 error when average scores were compared to standard values. Statistica software was used to perform statistical procedures.

Results

Results for prevalence of overweight people showed no significant difference between master swimmers and French population. Results for prevalence of obese people showed differences in proportion for female swimmers for age classes 50-59 and 60-69 years. For male swimmers, significant differences in proportion of obese people were reported for 30-39 and 60-69 years.
Table I  Prevalence of overweight and obesity by age-class and gender in master swimmers and in French reference group according Charles et al. (2008) (95% of confidence interval)

<table>
<thead>
<tr>
<th></th>
<th>Females</th>
<th></th>
<th>Males</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Master Swimmer (%)</td>
<td>Females References (%)</td>
<td>Master Swimmer (%)</td>
<td>Males References (%)</td>
</tr>
<tr>
<td>25-29 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overweight (%)</td>
<td>11.5</td>
<td>13.6</td>
<td>20</td>
<td>19.7</td>
</tr>
<tr>
<td>Obesity (%)</td>
<td>3.8</td>
<td>7.2</td>
<td>4</td>
<td>5.2</td>
</tr>
<tr>
<td>30-39 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overweight (%)</td>
<td>22.4</td>
<td>20.2</td>
<td>31.3</td>
<td>33.9</td>
</tr>
<tr>
<td>Obesity (%)</td>
<td>6.1</td>
<td>13.7</td>
<td>1.6*</td>
<td>9.3</td>
</tr>
<tr>
<td>40-49 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overweight (%)</td>
<td>16.4</td>
<td>22.1</td>
<td>41.2</td>
<td>40.6</td>
</tr>
<tr>
<td>Obesity (%)</td>
<td>6.6</td>
<td>13.7</td>
<td>7.1</td>
<td>13.4</td>
</tr>
<tr>
<td>50-59 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overweight (%)</td>
<td>28.1</td>
<td>29.2</td>
<td>45.6</td>
<td>45.1</td>
</tr>
<tr>
<td>Obesity (%)</td>
<td>1.8*</td>
<td>16.6</td>
<td>10.5</td>
<td>15.6</td>
</tr>
<tr>
<td>60-69 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overweight (%)</td>
<td>34.6</td>
<td>33.6</td>
<td>54.2</td>
<td>47.5</td>
</tr>
<tr>
<td>Obesity (%)</td>
<td>3.8*</td>
<td>17.7</td>
<td>4.2*</td>
<td>20.9</td>
</tr>
<tr>
<td>70-79 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overweight (%)</td>
<td>16.7</td>
<td>35.2</td>
<td>37.5</td>
<td>50.0</td>
</tr>
<tr>
<td>Obesity (%)</td>
<td>33.3</td>
<td>16.8</td>
<td>12.5</td>
<td>17.1</td>
</tr>
</tbody>
</table>

* Significant difference in repartition between master swimmers and standard population according to overweight and obesity (25 ≤ BMI < 30 kg/m² and BMI ≥30 kg/m²).

Results for PEF are presented in table II and showed higher pulmonary performances for female swimmers from 25 to 60 years in comparison with standard values (493 ± 70 l.min⁻¹ vs 441 ± 8 l.min⁻¹, 479 ± 66 l.min⁻¹ vs 445 ± 8 l.min⁻¹, 482 ± 77 l.min⁻¹ vs 429 ± 10 l.min⁻¹, 476 ± 71 l.min⁻¹ vs 407 ± 11 l.min⁻¹, for age classes 25-29, 30-39, 40-49, 50-59 respectively, p<.05). Only men from 40 to 50 years old performed significant higher PEF scores than normative values (658 ± 74 vs 623 ± 32, p<.05).

Table II  Peak flow expiratory (L.min⁻¹) comparison between master swimmers measures and estimated performances by age-class and gender according Nunn and Greg (1989)

<table>
<thead>
<tr>
<th>Years</th>
<th>Female</th>
<th>Male</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured PEF (L.min⁻¹)</td>
<td>Normative data (L.min⁻¹)</td>
</tr>
<tr>
<td>25-29</td>
<td>493 ± 70</td>
<td>441 ± 8*</td>
</tr>
<tr>
<td>30-39</td>
<td>479 ± 66</td>
<td>445 ± 8*</td>
</tr>
<tr>
<td>40-49</td>
<td>482 ± 77</td>
<td>429 ± 10*</td>
</tr>
<tr>
<td>50-59</td>
<td>476 ± 71</td>
<td>407 ± 11*</td>
</tr>
<tr>
<td>60-69</td>
<td>434 ± 89</td>
<td>377 ± 9</td>
</tr>
<tr>
<td>&gt;70</td>
<td>305 ± 107</td>
<td>334 ± 17</td>
</tr>
</tbody>
</table>

* Significantly different between measured PEF and estimated PEF with p<.05.

SF 36 variables significantly different between master swimmers and references values are presented in table III. Results showed higher health scores for female swimmers concerning physical limitations (92.3±17.5% vs 82.4±32.0%; 91.3±17.2% vs 76.6±36.9%; for age classes 45-54 years and 55-64 years respectively, p<.05) and vitality (66.1±15.8% vs 58.3±19.5%; 67.4±14.7% vs 58.2±19.9%; 69.4±15.6% vs 59.4±20.3%; 72.6±12% vs 59±21.4%; for age classes 25-34, 35-44, 45-54 and 55-64 respectively, p<.05). Results concerning pain perception showed lower scores for women swimmers (71.1±16.3 vs 79.4±20.3, for age class 35-45 years, p<.05). For male swimmers, results showed higher health scores for vitality (70.7±10.4 vs 62.9±19.9, 72.6±10.0 vs 62.9±20.3; for age classes 45 to 54 and 55-64.
respectively, p<.05) and lower scores for pain perception (77,5±17.4 vs 85,6±18.5; 71,7±20.1 vs 81,8±20.1; 74,6±13.6 vs 78,8±22.9, from 35 to 55 years).

<table>
<thead>
<tr>
<th>Table III</th>
<th>Variables of SF 36 significantly different with normative data by age and gender according Jenkinson et al. (1993)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Female Master Swimmer</td>
</tr>
<tr>
<td>Physical limitations</td>
<td></td>
</tr>
<tr>
<td>25-34</td>
<td>79,4±12.5</td>
</tr>
<tr>
<td>35-44</td>
<td>77,9±11.6</td>
</tr>
<tr>
<td>45-54</td>
<td>92,3±17.5*</td>
</tr>
<tr>
<td>55-64</td>
<td>91,3±17.2*</td>
</tr>
<tr>
<td>25-34</td>
<td>66,1±15.8*</td>
</tr>
<tr>
<td>Vitality</td>
<td></td>
</tr>
<tr>
<td>35-44</td>
<td>67,4±14.7*</td>
</tr>
<tr>
<td>45-54</td>
<td>69,4±15.6*</td>
</tr>
<tr>
<td>55-64</td>
<td>72,6±12*</td>
</tr>
<tr>
<td>25-34</td>
<td>72,7±21.1</td>
</tr>
<tr>
<td>35-44</td>
<td>71,1±16.3*</td>
</tr>
<tr>
<td>45-54</td>
<td>74,6±17.7</td>
</tr>
<tr>
<td>55-64</td>
<td>66,0±17.4</td>
</tr>
</tbody>
</table>

* Significant difference between master swimmer and standard values (p<0.05)

**Discussion**

The aim of the study was to assess global health benefits of practice swimming in master population involved in French national championships. The study design aimed to report physical and psychological parameters in master swimmers in order to compare them with standard values reported in French or European population. The hypothesis was that a competitive swimming practice increases all health parameters. Due to the large sample of participants (N= 490), this subsample of athletes can be considered as a representative sample of swimmers in French championships.

Results concerning BMI (kg.m\(^{-2}\)) showed significant lower prevalence of obese people for male and female swimmers for specific age classes. From this point of view, results corroborate results of Walsh et al. (2012) showing a lower prevalence for obesity in world master games swimmers in comparison with national population of Australia. No significant difference was noted for prevalence of overweight people between master swimmers and French population suggesting that swimming training was not linked with high weight loss. Nevertheless, it is possible that, due to athletic activity, a reduced fat to lean body mass ratio was more likely in the national French master swimmers than for the general population. Moreover, there could be a buoyancy advantage with fat deposits on certain regions of the body for swimmers. According to Gwinup (1987), swimming is not the most effective form of exercise in order to loss weight which could explain the lower prevalence for obese people because of a high physical activity but not sufficient to decrease weight under the cut of defined by the WHO (BMI< 25 kg.m\(^{-2}\)). It should be noted that the issue of causation must also be considered. Namely, the question of whether competing in national French master swimmers promoted reduced obesity and lowered associated health risks, or whether individuals with lower BMI’s participated in Masters swimming Championships by preference.

PEF results showed significant higher values for female master swimmers than for related theoretical values. For male master swimmers, no significant difference were noted whereas all mean values were higher than references values. It is worth noticing that predictive values corresponded to a health level of lung function. Despite the chloramine environment of practice, competitive swimming appeared to be effective to develop functions of respiratory especially for female swimmers. These results corroborate conclusions of several studies (Courteix et al. 1997; Mehrotra et al. 1997; Doherty & Dimitriou 1997) showing the effect of swimming training in respiratory muscle. Indeed, swimming
exercise affects lung volume measurements as respiratory muscles of swimmers are required to develop greater pressure as a consequence of immersion in water during respiratory cycle, thus may lead to functional improvement in these muscles leading to an improvement in lung functions. The fact that female swimmers develop higher performances than predictive values could be explained by the addition of this kind of exercise with a higher physical activity than their national counterparts.

Scores from SF 36 tests were conducted in order to evaluate psychological and social health. Results showed no significant difference between master swimmers and reference values for social functioning, emotional problem, mental health and general perception of health. Subjective perception of vitality was significantly higher for all female swimmers and for high age classes for male swimmers (from 45 to 65 years old). These results corroborate partially study of Acree et al. (2006) showing better scores in bodily pain, vitality and social functioning by comparing active vs sedentary old people. The competitive swimming practice seems to impact in the same way vitality but generate opposite effect in perception of bodily pain with significant lower scores for female and male swimmers. High quantity in training with a sport including high proprioception of the body appeared to decrease perception of health from a subjective perception of pain point of view.

**Conclusion**

It is commonly assumed that a long term adherence to physical activity improves indices of general health. In French master swimmers involved in national championships, it was hypothesised that all indices of health concerning physical, social and mental domains were higher than values of general population within France or Europe. Results showed significant high health scores in several domains, but lower scores in perception of bodily pain. Further investigations is needed to specify the links between competitive swimming practice and health benefits.

**References**


6 Physiology

Effect of an exhaustive swim exercise on isometric peak torque and stroke parameters

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Introduction

In swimming, biomechanical aspects, such as drag and the level of application of propulsive force as well as physiological aspects associated to the energy production are important for performance (Hollander et al. 1986). Some technical parameters such as the stroke rate (SR) and stroke length (SL) have shown significant changes throughout competitive races (Craig et al. 1985) as well as constant-speed tests (Dekerle et al. 2005; Alberty et al. 2009; Pelarigo et al. 2011; Oliveira et al. 2012), which have been attributed to the compromised capacity to generate force to overcome drag (Craig et al. 1985). Thus, the changes in swim technique have been attributed to fatigue (i.e., the reduced capacity to produce force) (Gandevia 2001).

Indeed, decrements on power, speed and SR have been demonstrated during swim exhaustive tests (Toussaint et al. 2006). Moreover, Aujouannet et al. (2006) have shown significant changes in SR and SL throughout an exhaustive test and maximal isometric force, performed in a swim bench. At similar swim conditions, Ikuta et al. (2012) verified significant reduction of electromyographic activity of biceps brachii and triceps brachii muscles during the test. However, no studies have determined the relationship between changes in muscle strength and the changes in swim technique in exhaustive swim tests.

In front-crawl swimming, the propulsion is produced mainly by arm movements (Hollander et al. 1987). Among the main muscles utilised for propulsion are the triceps brachii and biceps brachii, which are essential during the underwater phase of the stroke (Clarys 1983). Indeed, Figueiredo et al. (2013) have demonstrated significant changes in the amplitude (triceps brachii and biceps brachii) and frequency (triceps brachii) electromyography parameters throughout a maximal 200-m front crawl swim test. Thus, the objective of this study was to correlate the changes in the isometric peak torque (IPT) of elbow flexors (EF) and elbow extensors (EE) and the stroke parameters (i.e., SR and SL) induced by an exhaustive swim. It was hypothesised that a direct relationship might exist between the changes in swim technique and force.

Method

Subjects

Eight regional-level male swimmers (25.6 ± 6.7 yr., 1.78 ± 0.1 m and 74.9 ± 11.1 kg) volunteered and gave written informed consent to participate in the present study, which was approved by the university’s ethics committee. Participants were training for at least 4 years (5 training sessions a week; 20 km per week during the 2 weeks prior testing), and were competing in regional level meets over middle to long distances (200 to 1500 m). The participants were instructed to refrain from intense training sessions and to have refrained from using caffeine containing food or beverages, drugs, alcohol, cigarette smoking, or any form of nicotine intake at least 24 h before the experimental sessions.
Experimental design
The subjects performed on different days the following tests: 1) familiarisation to the dynamometer; 2) a 400-m swim trial to determine the aerobic performance (V400); 3) two isometric maximal voluntary contractions of 3 s to determine IPT of EF and EE. These tests were performed before and immediately after an exhaustive constant-speed test at 100%V400.

Material and measurements
All swim tests were performed in a 25-m outdoor swimming-pool (29°C) from a push start. The tests to determine force of EF and EE muscles were performed in a Biodex isokinetic dynamometer (Biodex System 3, Biodex Medical Systems, Shirley, N.Y.).

Determination of aerobic performance
The participants were instructed to swim the distance of 400 m as quickly as possible using the front crawl stroke; they were not instructed to swim at a constant speed. The time taken to swim the distance was recorded using a manual chronometer.

Determination of time to exhaustion
The constant-speed test was performed at 100%V400 until voluntary exhaustion or when the participant did not keep the imposed swim speed, even with verbal and visual stimulus. During the exhaustive constant-speed test the swimming speed was controlled using a mp3 player attached to the goggles of the swimmer (MP120B/F, Oregon). A regular audible signal enabled the swimmer to maintain the target pace. Red marks were traced every 5 meters on the bottom of the pool and the swimmers were instructed to pass their feet across on each ‘beep’. The time to exhaustion was recorded using a manual chronometer.

Stroke parameters
The time to complete 5 stroke cycles was recorded to calculate the SR. This procedure was performed at the beginning (between the first 25th and 50th m) and the end (last 25 m swam at the imposed speed) of the constant-speed test. The speed of 25 m at these moments of the test was recorded using a manual chronometer and the SL was calculated as the ratio between speed and SR.

Statistical analysis
Data are presented as the mean ± SD. The distribution of all dependent variables was examined by Shapiro-Wilk test. A Student’s t test for paired samples was used to compare pre- and post-test conditions for each variable. The correlation between the changes in IPT and stroke parameters was performed using Pearson correlation test. The significance level was set at p < 0.05.

Results
The mean ± SD values of V400 and time to exhaustion were 1.27 ± 0.11 m.s⁻¹ and 194.9 ± 39.6 s, respectively. There were significant reduction in IPT of EF (15%) and EE (16%) after the exercise (p < 0.05) (Figure 1).
Figure 1  Isometric peak torque (IPT) of elbow flexors (EF) and elbow extensors (EE) before (Pre) and after (Post) the exhaustive constant-swim test

Figure 2  Stroke length (SL) and stroke rate (SR) values throughout the exhaustive constant-speed test

Note: * p < 0.05 in relation to Pre. N = 8
The SR and SL were changed from the beginning to the final part of the test (p < 0.05) (Figure 2). No significant correlation ($r = -0.55 - 0.29$, $p > 0.05$) was found between the changes in IPT and stroke parameters (Figure 3).

**Discussion**

The main finding of this study was that an exhaustive swim exercise performed at V400 generated significant changes in swim technique parameters and isometric strength of EE and EF muscles. However, at least at the conditions of our study, these changes seem not be associated.

With regard to the swim technique parameters, our data are in accordance with those obtained by Alberty et al. (2009), that have demonstrated reduced SR (8.7%) and increased SL (7.7%) values from the beginning to the end of an exhaustive constant-speed test performed at 100%V400. In this study, these changes were also observed during the tests performed at 95% and 110%V400. The reduction of SL has been considered representative of the decrease of the work per stroke and propulsive efficiency (Toussaint & Beek 1992).

Changes in parameters related to power and force have been also observed during and after exhaustive swim exercises. Toussaint et al. (2006) analyzed and compared the response of speed, stroke parameters (FB e CB) and mechanical power output during maximal 100-m swim tests. There was significant reduction of power (24%), measured in MAD system, swim speed (12.4%) and SR (10.6%) during the tests. In other study, Aujouannet et al. (2006) analyzed the effect of 4 x 50 m maximal test, in stroke parameters, isometric force, muscular activity and blood lactate concentration. There was significant reduction of swim speed (14%), SR (8.8%) and isometric force (13.8%). Additionally, the mean power frequency of EE and EF at maximal voluntary contraction was decreased after the swim test.
Monteil et al. (1994) suggested that the reduction of propulsive force can decrease the hand and swim speeds. In the study of Ikuta et al. (2012) the authors have verified reduced values of swim speed, arm angular velocity of shoulder flexion and electromyographic activity of EE and EF during a maximal 4 x 50 m swim test. The changes of swim speed and mean amplitude value of the electromyogram for EF were significantly correlated. In our study, the reduction of muscular force of EE (15%) and EF (16%) was similar to that obtained by Aujouannet et al. (2006), on the maximal isometric shoulder flexion contraction obtained in a swim bench.

During front crawl swim, the EF and EE muscles are among the main muscles utilised during the stroke. The reduced values of force of these muscles after the swim test demonstrate the occurrence of fatigue. The changes in swim technique during the exhaustive test are in accordance with other studies, during constant-speed tests. However, at the conditions of our study, the changes in swim technique parameters and muscular force were not significantly related. This can be explained, at least in part, by some aspects related to the force measurement conditions. The isometric contraction has been considered a well-controlled condition to measure muscle force. However, it might not represent some specific aspects of the movements utilised during the exhaustive swim exercise, even utilising similar muscle groups during the evaluation. In addition to the contraction type, factors such the limb position, subject’s position and posture might help to explain our results.

Conclusion

Although a high-intensity exhaustive test may generate significant changes in torque and swim technique, the fatigue measured at isometric condition might not explain the changes in stroke parameters.

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Bone mineral density differences between swimmers and soccer players in different age groups

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Keywords: BMD, swimming, football, age groups

Introduction

During childhood and adolescence, bone mineral density (BMD) increases until the peak bone mass is reached in adulthood. Physical activity has been proposed as a major determinant of BMD. The osteogenic effect of exercise can be attributed mainly to the impact and mechanical loads applied to the bone; however, not all physical activities have the same effects on bone. Duration and intensity are factors which will affect the osteogenic stimulus produced [1, 2, 3].

Recent literature reviews have shown that high impact sports seem to be more osteogenic than nonimpact sports such as swimming or cycling, in children [4], young adults [4, 5] or older adults [6]. Some studies showed that athletes from other sports presented BMD values much higher than swimmers [7, 8]. A lot of investigations have been produced approaching this theme; nevertheless, results among studies remain disparate [7-12]. Therefore, further investigations in this area are needed in order to elucidate the effect of swimming on BMD.

Purpose

The aim of the study was to evaluate the BMD of children, teenagers and adults, who train in soccer and swimming disciplines.

Methods

After written informed consent was obtained, 117 male volunteers were recruited being 38 soccer players (SP), 33 swimmers (SW) and 46 forming a control group (CG). The control group was composed by sedentary individuals. The subjects were divided according to the age in three groups: children 7 to 10 y (n=50), teenagers 11 to 17 y (n=41), and adults 18 to 30 y (n=36). The basis of the swimming training program was children: swimming techniques, flexibility and games, 1.0-1.5 hours/day, 5 days/week; teenagers: swimming training and dry land sessions including stretch cords, dumbbells, medicine-ball, circuit training, 1.5-2.0 hours/day, 5-6 days/week; adults: swimming training and dry land sessions including strength and circuit training, 2-3 hours/session, 5-6 days/week. Soccer players trained in average, for 1-3 hours/day, 3-6 days/week, including physical, technical and tactical training. BMD and body fat percentage (%BF) were measured using dual-energy absorptiometry (DXA) (Lunar Prodigy Advance®—GE Healthcare, Madison, USA). One Way Anova for multiple analyses within and between the studied groups was performed (SPSS 19.0, IBM, Chicago, USA).

Results

Physical characteristics for height (cm), weight (kg), body mass index (kg/m²) and body fat percentage (%BF) are showed in Table 1.
Table 1
Physical characteristics mean values and standard deviation of the studied sample

<table>
<thead>
<tr>
<th>Group</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>BMI (kg/m²)</th>
<th>BF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP children</td>
<td>134.6 ± 7.8</td>
<td>33.5 ± 7.4</td>
<td>18.5 ± 3.6</td>
<td>18.0 ± 12.3</td>
</tr>
<tr>
<td>SP teenagers</td>
<td>165.5 ± 10.8</td>
<td>59.1 ± 15.7</td>
<td>21.0 ± 4.2</td>
<td>16.0 ± 7.0</td>
</tr>
<tr>
<td>SP adults</td>
<td>177.5 ± 9.8</td>
<td>71.7 ± 12.4</td>
<td>22.6 ± 2.4</td>
<td>9.3 ± 3.2</td>
</tr>
<tr>
<td>SW children</td>
<td>134.6 ± 7.8</td>
<td>33.5 ± 7.4</td>
<td>18.5 ± 3.6</td>
<td>24.2 ± 12.3</td>
</tr>
<tr>
<td>SW teenagers</td>
<td>163.5 ± 11.0</td>
<td>52.4 ± 10.6</td>
<td>19.4 ± 2.0</td>
<td>13.5 ± 5.0</td>
</tr>
<tr>
<td>SW adults</td>
<td>172.7 ± 9.2</td>
<td>73.9 ± 8.6</td>
<td>24.8 ± 2.4</td>
<td>13.8 ± 6.3</td>
</tr>
<tr>
<td>CG children</td>
<td>130.0 ± 9.2</td>
<td>30.7 ± 7.1</td>
<td>18.0 ± 2.7</td>
<td>23.7 ± 9.7</td>
</tr>
<tr>
<td>CG teenagers</td>
<td>157.1 ± 11.3</td>
<td>50.7 ± 13.5</td>
<td>20.3 ± 3.1</td>
<td>24.7 ± 9.5</td>
</tr>
<tr>
<td>CG adults</td>
<td>177.4 ± 5.6</td>
<td>76.3 ± 11.4</td>
<td>24.3 ± 3.3</td>
<td>23.8 ± 8.9</td>
</tr>
</tbody>
</table>

SP = soccer players, SW = swimmers, CG = control group.

BMD mean values of the three groups are summarised in Table 2.

Table 2
BMD (g/cm²) mean values and standard deviation of children, teenagers and adults for the soccer, swimming and control groups

<table>
<thead>
<tr>
<th>Age group</th>
<th>Soccer</th>
<th>Swimming</th>
<th>Control group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Children</td>
<td>0.96 ± 0.07</td>
<td>0.93 ± 0.05</td>
<td>0.86 ± 0.05</td>
</tr>
<tr>
<td>Teenagers</td>
<td>1.19 ± 0.16</td>
<td>1.05 ± 0.07</td>
<td>1.02 ± 0.14</td>
</tr>
<tr>
<td>Adults</td>
<td>1.41 ± 0.87*</td>
<td>1.26 ± 0.08*</td>
<td>1.23 ± 0.11*</td>
</tr>
</tbody>
</table>

The significance level was set at P ≤ 0.05, and * indicate difference between children and adults of the same group.

P = 0.371, P = 0.093 (between SP and SW for teenagers and adults, respectively)

Discussion

In the present study no differences were found in mean BMD values between swimmers, soccer players and CG. Regarding the studies which evaluated bone mass in swimmers, it is essential to take into account two points. First the type of device used for the bone analysis, and second the factors affecting bone mass like hormonal profile, nutrition (especially calcium intake and vitamin D status), gender, age, maturational stage, and past activity and present training characteristics [3].

In the 1970s a study which compared bone mass between swimmers, other athletes and in a non-athletic control group (CG) of young adults found a higher BMD in the femur of all the athletes in comparison with the CG; however, when compared with the CG, swimmers had similar BMD values [13]. Subsequent studies comparing swimmers and individuals who performed less than three hours of physical activity per week corroborated the findings of similar BMD values between swimmers and non-athletic male and female subjects, in children [14-18], adolescents [1, 9, 19-23] young adults [24-30] or elderly populations [24]. Our study is in accordance with these studies.

Notwithstanding, some of the studies conducted on swimmers found higher arm BMD or BMC in this group than in non-athletic individuals [7, 28, 31]. This effect has been attributed to the force applied by the forearm’s muscle during exercise [32]. A site-specific effect on bone mass is described in the literature; especially in tennis player [32, 33] and lean muscle mass has been show as an important predictor of BMD [34, 35].

However, as expected, mean BMD values were different between children and adults (Table 2), as all children were in the prepubertal stage [35].

Training intensity, type and duration (hours/week) may also differ between groups that perform the same sport modality and train for a similar number of hours. Different intensities can result in different performances and also in different body composition and bone adaptations [3], as found in the present study. It is also important to take into account the increased capacity of the anaerobic system and the strength in adults in comparison to children and adolescents [36].
Conclusion
No difference on the BMD was found between swimmers, soccer players and control group. Independent of exercise, BMD was significantly different between children and adults, which probably represents expected biological process.

References
Fatigue of the shoulder’s internal rotators following a 200-m all-out swim

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Keywords: fatigue, isokinetic dynamometer, torque – joint angle relationship

Introduction
A high prevalence of shoulder pain has been reported for competitive swimmers with severe cases potentially leading to functional impairments and termination of participation (Tate et al. 2012). Greater swimming exposure defined by distance or time spent swimming, characterises symptomatic groups (Tate et al. 2012; Sein et al. 2010) who present, among other physical impairments, weakness of the internal and external rotation strength (Tate et al. 2012; Beach et al. 1992; Sein et al. 2010). Pain vs pain-free swimmers, and within the pain group, symptomatic vs non symptomatic shoulders, are characterised by reduced concentric and eccentric internal rotational torques leading to greater external-to-internal rotational strength ratios (Bak and Magnusson 1997).
Muscle fatigue of the internal rotators and the pectoralis major in particular, affects dynamic stabilisation of the humeral head which may lead to microtrauma (Wanivenhaus et al. 2012). During the arm stroke in freestyle, the overhead arm action is produced by the scapular and rotator cuff muscles. These muscles work in synergy to deliver movement whilst establishing stability (McMaster 1999). Shoulders are internally rotated during the hand entry, late pull-through phase (90° flexion to hand exit) and recovery phase, i.e. all but one phase of the stroke (Wanivenhaus et al. 2012). Studies measuring electromyographic responses during all-out front crawl swimming have reported increases in activities of upper-limb muscles including internal rotators such as the pectoralis major as fatigue developed (Rouard 2010; Ikuta et al. 2012; Figueiredo et al. 2013). This was suggested to reflect the recruitment of additional motor units in an attempt to maintain the swimming speed (Rouard 2010).

Most investigations on muscular strength and endurance report the use of isokinetic dynamometers to ensure validity and reliability in torque measurement (Baltzopoulos and Brodie 1989). Torque can be measured during short voluntary contractions performed (a) maximally (MVC) and (b) at different, set (isometric), joint angles. Pre- and post-exercise measurements allow for the maximal torque – joint angle relationship to be assessed in both fresh and fatigued states of muscle groups [human elbow flexors, (Philippou et al. 2004; Prasartwuth et al. 2006)]. Fatigue has been shown to alter the inverse-U shape of this relationship with a shift to the right of the optimal joint angle alongside a fatigue-reduced peak torque (Philippou et al. 2004; Prasartwuth et al. 2006).

Decrements in force production have been observed during or following all-out swimming (Aujouannet et al. 2006; Rouard 2010). To our knowledge, no study has reported the effect of a fatiguing swim on the ability for a muscle group, the internal rotators in the present study, to generate force across a range of joint angles. A significant decline would ascertain the presence of fatigue (Taylor & Gandevia 2008). Muscular fatigue has often been put forward as the main explanatory mechanism underpinning the changes in the stroking parameters observed during a 200-m all-out swim (Alberty et al. 2005; Figueiredo et al. 2013). The aim of this study was therefore to quantify the loss of isometric torque during MVCs performed prior and following a 200-m all-out swim. Three different joint angles for the internal rotators were tested. Changes in swimming speed, stroke rate and stroke length were also quantified throughout the 200-m all-out swim. It was hypothesised that maximal isometric torque would be reduced post-exercise. This evidence of fatigue should be concomitant with a reduction in speed, stroke length and stroke rate during the 200-m swim.

**Method**

**Participants**

10 trained swimmers, 5 male and 5 female (mean ± SD 20 ± 1 years, 171 ± 12 cm, 70.2 ± 11.3 kg) took part in this study. Each participant had a minimum of 5 years of competitive experience and trained and competed with their university team when the study took place (5 sessions per week, 60-90-min sessions).

**Equipment**

All MVCs were performed on an isokinetic dynamometer (Con-Trex multi-joint module; CMV AG; Switzerland) located 12 meters from the edge of the 25-m pool (range: 27.8 – 28.0° water temperature, 27.5–28.5° air temperature). The arm height, position and handgrip placement were set to the specifications of the individual following the user guide recommendations. The position was kept consistent from the initial familiarisation visit. Subjects were positioned adjacent to the dynamometer in a supine position and maximal isometric strength of the right shoulder’s internal rotators was measured with the arm at the side in 90° of abduction and elbow supported and positioned in 90° of flexion (Figure 1). The shoulder was placed in the anatomical zero position (0°), or in a rotated position (+45° or −45° from the anatomical zero). The upper trunk was firmly strapped to the seat. The weight of the upper limb was recorded and all measurements were corrected for gravity.
Three synchronised side-view cameras (Canon Legria HFS 200; shutter speed: 1/2000 s; sampling frequency: 50 Hz) were set on poolside to film each 200-m swim from above (0 m, 12.5 m and 25 m). DartFish (Version 6.0, TeamPro) was used for subsequent analysis of the stroking parameters.

**Experimental design**

Participants attended 4 sessions of testing (~ 72 hours apart). The first session was a familiarisation to (1) the muscular testing procedure on the isokinetic dynamometer and (2) the pool to dynamometer transition so that the time between the end of the swim and the first isometric MVC could be minimised and standardised (2 minutes). The following three sessions were randomly assigned and consisted in three pre-swim MVCs, a 200-m all-out swim, and three post-swim MVCs (Figure 1). One joint angle was tested per session (0°, -45° or 45° from anatomical zero). The warm-up prior the pre-swim MVCs consisted in 7 x 5-s voluntary contractions performed at 25% (x 2), 50% (x 2), 75% (x 2) and 100% effort (x 1) with 20-sec of recovery in-between. The warm-up prior the 200-m swim was also standardised.

**Data analysis**

Average torque was recorded for each MVC with the highest score from the three attempts recorded as 100% MVC. Swimming speed (m.sec⁻¹) was calculated from the measure of the time taken to swim a length. Stroke rate (cycles.min⁻¹) was computed from the time to complete three stroke cycles with 3 values averaged per length. Stroke length (m.cycle⁻¹) was calculated as the speed / stroke rate ratio.

**Statistical analysis**

All statistical procedures were performed using SPSS (version 15.0, Chicago, USA) with the null hypothesis rejected at an alpha level of 0.05. For each set of data, normal distribution (Kolmogorov-Smirnov test) was verified. The compound symmetry, or sphericity, was checked using the Mauchly’s test for comparisons of more than two data sets. A two-way ANOVA with repeated-measures was performed to identify pre- to post- x joint angle differences in torque as well as changes in the stroking parameters over the 200-m swim. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse–Geisser procedure. Significant differences were followed up using planned pair-wise comparisons employing the Bonferroni corrected post hoc test. Relationships were explored using Pearson’s product-moment correlation. Data are reported as mean ± SD unless stated otherwise.

**Results**

The mean speed recorded over the 200-m swims was 1.30 ± 0.13 m.s⁻¹. Table 1 presents the values for speed, stroke rate and stroke length for the first and last 50-m block as well as mean values for each 200-m performance. Significant losses in speed (-11 to 13%; F=103.0, P<0.01), stroke rate (-6 to 8%; F=30.0, P<0.01) and stroke length (-5%; F=12.5, P<0.01) were found when comparing the last to the first 50-m block. No different was depicted between the three performances (P>0.05).
Table 1  Changes in the stroking parameters during the three 200-m performances

<table>
<thead>
<tr>
<th>Stroking parameter</th>
<th>Condition</th>
<th>First 50 m</th>
<th>Fourth 50m</th>
<th>% change from first to last 50 m</th>
<th>Average over the 200 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (m.sec⁻¹)</td>
<td>-45°</td>
<td>1.43 ± 0.12</td>
<td>1.27 ± 0.11 *</td>
<td>-11 ± 3%</td>
<td>1.30 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>0°</td>
<td>1.46 ± 0.13</td>
<td>1.26 ± 0.10 *</td>
<td>-13 ± 5%</td>
<td>1.31 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>+45°</td>
<td>1.43 ± 0.11</td>
<td>1.26 ± 0.10 *</td>
<td>-12 ± 4%</td>
<td>1.30 ± 0.11</td>
</tr>
<tr>
<td>Stroke rate (cycles.min⁻¹)</td>
<td>-45°</td>
<td>38.8 ± 6.0</td>
<td>36.0 ± 4.2 *</td>
<td>-6 ± 7%</td>
<td>36.3 ± 4.5</td>
</tr>
<tr>
<td></td>
<td>0°</td>
<td>39.7 ± 4.6</td>
<td>36.3 ± 3.6 *</td>
<td>-8 ± 4%</td>
<td>36.8 ± 3.9</td>
</tr>
<tr>
<td></td>
<td>+45°</td>
<td>39.2 ± 4.1</td>
<td>36.5 ± 3.8 *</td>
<td>-7 ± 6%</td>
<td>36.9 ± 3.9</td>
</tr>
<tr>
<td>Stroke length (m.cycle⁻¹)</td>
<td>-45°</td>
<td>2.25 ± 0.36</td>
<td>2.13 ± 0.21 *</td>
<td>-5 ± 6%</td>
<td>2.17 ± 0.24</td>
</tr>
<tr>
<td></td>
<td>0°</td>
<td>2.23 ± 0.25</td>
<td>2.10 ± 0.16 *</td>
<td>-5 ± 4%</td>
<td>2.15 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>+45°</td>
<td>2.20 ± 0.22</td>
<td>2.08 ± 0.18 *</td>
<td>-5 ± 6%</td>
<td>2.13 ± 0.18</td>
</tr>
</tbody>
</table>

* Significantly different with the first 50 m (P<0.01)

Figure 2 presents the changes in torque measurements. Maximal torque recordings were significantly lower after the 200-m swim (F=217, P<0.01). An angle effect was also found (F=46.3, P<0.01) with values recorded at -45° and 0° not significantly different (P>0.05) but significantly greater than those recorded at +45° (P<0.01).

No significant swim x joint angle interaction effect was found (F=1.32, P=0.35). The loss in maximal torque was therefore not joint angle–dependent and ranged from -13 ± 11% or -3.4 ± 3.1 Nm for the -45° angle, to -17 ± 12% or -4.7 ± 4.9 Nm for the 0° angle (-16 ± 16% or -2.4 ± 2.2 Nm for the +45° angle).

The loss in maximal isometric torque from pre- to post-swim was not significantly related to the loss in any of the stroking parameters when comparing the first to the last 50m (P>0.05).

Discussion

Muscular fatigue, or a loss in the ability for a muscle group to generate force (Taylor & Gandevia 2008) has been put forward as an explanatory mechanism underpinning the reduction in stroke length observed above Maximal Lactate Steady State (Dekerle et al. 2005) and changes in stroking parameters during a 200-m all-out swim (Alberty et al. 2005; Figueiredo et al. 2013). The present study demonstrates the occurrence of muscular fatigue following a 200-m all-out swim with a loss of
internal rotators’ strength within the range of 13 to 17%. This is consistent with the report of a 13% decrease in MVC scores during a shoulder’s flexion (90° arm-trunk angle) performed post a broken 4 x 50-m swim (Aujouannet et al. 2006). Greater loss in force production during isometric MVCs have been reported in laboratory-based studies following exhaustive exercise [knee extension (Froyd et al. 2013; Fernandez-Del-Olmo et al. 2013)]. While laboratory-based studies can lead to greater levels of muscular fatigue (30-35% depending on the fatiguing task), our 200-m performance was open-ended and self-paced. Furthermore, the pool to dynamometer transition time inherent to the testing procedure would also allow for force to be recovered as a passive recovery of 2 minutes has been shown to enhance MVCs outputs by ~30% or from 50% to 65% of pre-testing values in knee extensors (Froyd et al. 2013). The actual loss of strength is very likely to be greater immediately following the 200-m swim. But despite the limitation of the present study, muscular fatigue was still present following the 200-m all-out swims.

No sets of normative data could be found for maximal torque measurements during isometric MVCs of shoulder’s internal rotators in swimmers. An inverse U-shape curve was expected for the maximal torque – joint angle relationship (Figure 2). Interestingly, no significant difference was found between two joint angles with a decrease in maximal torque observed at +45° only. Similarly, Rouard et al. (2006) did not find any between-angle differences in maximal isometric force for the shoulder’s flexion recorded in swimmers (30°, 90°, 120°). In the present study, with small differences between the 0° and -45° angles in the present study, the optimal angle for peak torque is likely to lie between these two angles.

Extremely fatiguing protocols of repeated eccentric and isometric contractions have been shown to affect the maximal torque – joint angle in elbow flexors with a flatter and right-shifted curve following fatigue (Prasartwuth et al. 2006; Philippou et al. 2004). Two hours following eccentric contractions (performed until voluntary torque had decreased by ~40%), peak torque was still reduced by 40% with a greater optimal joint angle in the elbow flexors [+17° from 93° in the fresh state; (Prasartwuth et al. 2006)]. Further studies could investigate the modelling of the maximal torque – joint angle relationship pre- and post- a fatiguing swimming exercise to complement the present findings.

Conclusions

The internal rotators of the right shoulders do lose their ability to voluntarily produce force following a 200-m all-out swim, by around 15% (2 minutes post-swim). Despite between-angle differences in the torque values with lower scores (-30 to 35%) recorded at +45° when compared to 0° and -45°, a similar level of muscular fatigue occurred across the -45° to +45° range of joint angle investigated.

The effect of fatigue on the ability for the internal rotators of the right shoulder to produce force is not joint angle-dependent.

References


The present study analysed the oxygen uptake slow component (VO$_{2SC}$) of front crawl swimming along an incremental swimming protocol, using a multi-exponential function. Eleven well-trained swimmers (20.4±2.5 yrs, 1.80±0.06 m and 74.1±4.12 kg) performed a front crawl incremental protocol of 7×300 m until exhaustion (with increments of 0.05 m/s and 30s rest intervals between steps). VO$_{2}$ was collected bxb using a portable gas analyzer (K4b2) connected to the new AquaTrainer respiratory snorkel (both from Cosmed, Italy). VO$_{2SC}$ was assessed using a double exponential regression model with exponential terms amplitudes, time delays and time constants representing the VO$_{2}$ kinetics fast (1) and slow (2) components. In addition, the calculation of the VO$_{2SC}$ values through the fixed interval method was also conducted by subtracting the average VO$_{2}$ observed in the last 40s of each step by
the average VO\textsubscript{2} observed in the 3rd min of exercise. A paired T-test was used to compare both methods along the incremental test (p ≤ 0.05). The multi-exponential model showed that the VO\textsubscript{2sc} was above 200 mL min\textsuperscript{-1} from the 5th until the 7th step of the incremental protocol, i.e., intensities above the anaerobic threshold. Differences were observed in mean values of VO\textsubscript{2sc} obtained by the mathematical modelling and the fixed interval method in every step of the protocol (P ≤ 0.05, d > 0.76). It was concluded that in well-trained front crawl swimmers VO\textsubscript{2sc} exists in a significant faction at exercise intensities above the anaerobic threshold. This means that at heavy and severe swimming intensities the higher work rates implied the recruitment of faster but more easily fatigable fibers, which could lead to less efficient processes, and consequently, to higher VO\textsubscript{2sc} mean values.

**Introduction**

The magnitude and nature of the adjustment of the oxygen uptake (VO\textsubscript{2}) kinetics in a step workload has three components: (i) the first phase, the cardio-dynamic component, corresponds to a fast increase in alveolar VO\textsubscript{2}, allowing a transient plateau of 15-20 s after on-transition (Hughson et al. 1988); (ii) the second phase, or fast component, is linked to muscular VO\textsubscript{2} (Mole and Hoffmann 1999), which increases exponentially up to an alleged steady-state, taking about 2-3 min on healthy subjects (Burnley et al. 2002); and (iii) the third phase, depending on the exercise intensity, could evidence a VO\textsubscript{2} plateau or (if exercising above the anaerobic threshold) a slow component (VO\textsubscript{2sc}), expressing the raising of VO\textsubscript{2} above the predicted demand (Burnley and Jones 2007).

The VO\textsubscript{2sc} has been traditionally assessed by the fixed intervals method (Phillips et al. 1995), i.e., by the differences of minute average VO\textsubscript{2}, particularly between the last and the 3rd min (Mole and Hoffman 1999) or the 2nd min of exercise (Koppo and Bouckaert 2002). Agreeing that this method is inclinable to error (Mole and Hoffman 1999), the VO\textsubscript{2sc} has alternatively been assessed by mathematical modelling, as the amplitude of an exponential function (Barstow and Mole 1991).

In swimming, the studies addressing the VO\textsubscript{2} kinetics and the VO\textsubscript{2sc} are scarce and recent, appearing only when portable telemetric metabolic measurement carts began to be available for aquatic environment research. The pioneer studies on the topic presented some limitations, once the VO\textsubscript{2sc} was assessed using fixed intervals methods, a simple methodology that does not yield reliable data (especially when evaluating elite swimmers), tending to underestimate the VO\textsubscript{2sc} values (e.g. Fernandes et al. 2003). Moreover, some of this studies were performed in swimming flume (not in ecologic swimming conditions; Demarie et al. 2001), which may impose some constraints when compared with free swimming in a standard pool (Fernandes et al. 2008).

In addition, it was demonstrated in running (Reis et al. 2007) and cycling exercise (Billat et al. 1998) that the VO\textsubscript{2sc} is sensible to the rate of blood lactate accumulation and that the exercise intensity immediately above the anaerobic threshold generally marks the appearance of the VO\textsubscript{2sc} phenomenon. However, this is very scarcely identified in swimming, especially during a front crawl incremental protocol, which is frequently used for evaluating swimmers and to control the training process (Pyne et al. 2001; Fernandes et al. 2006).

As findings about VO\textsubscript{2sc} during incremental swimming could be of great interest and application for the training process, the present study aimed to analyse the VO\textsubscript{2sc} phenomenon across low to severe swimming intensities, using a mathematical approach. It was hypothesised that the VO\textsubscript{2sc} would appear at steps above the anaerobic threshold (i.e., at the heavy and severe intensity domains), but not bellow and at this threshold (i.e., at low to moderate intensities). Complementarily, a comparison between the multi exponential function with a fixed interval method was carried on.

**Methods**

Eleven well-trained swimmers (20.4±2.5 yrs, 1.80±0.06 m and 74.1±4.12 kg) voluntary participated in the present study. Participants were completely informed about the procedures and demands of the study and signed a written informed consent approved by the Institutional Ethics Committee.
Procedures
The experimental moments took place in a 25 m indoor swimming pool (1.90 m deep) with (mean ± SD) 27.3 ± 0.1 °C water temperature, 28.5 ± 0.2 °C room temperature and 55.2 ± 0.4% humidity from 8:00 until 12:00 am. After a 20 min duration moderate intensity warm-up, swimmers performed a front crawl intermittent incremental protocol specific for maximal VO₂ assessment (VO₂max), consisting of 7x300 m front crawl, with increments of 0.05 m/s and 30 s resting intervals, until voluntary exhaustion (Fernandes et al. 2011). The speed of the last step was established according to each swimmer’s 400 m front crawl time at the moment of the experiments, with successive 0.05 m/s being subtracted allowing the determination of the mean target speed for each step. A visual pacer with flashing lights on the bottom of the pool (GBK-Pacer, GBK electronics, Aveiro, Portugal) was used to help maintaining the pre-defined individualised paces. In-water starts and open turns were performed due to the constraints of the ventilatory evaluation.

Assessment of gas pulmonary exchange
Respiratory gas exchange during the incremental protocol was assessed breath-by-breath with a portable gas analyser (Cosmed K4b2, Cosmed, Italy) connected to recently developed snorkel and valve system (Aquatrainer, Cosmed, Italy; Baldari et al. 2013). The K4b2 apparatus was calibrated following a standard certified commercial gas preparation (cf. K4b2 user manual) and measured the atmospheric pressure and ambient temperature (with the relative humidity being manually reported before each test). In addition, the temperature of the expired gas detected at the turbine was at measured the end of each 300 m step with an infrared thermometer (Kramer, Med.Ico).

Assessment of blood lactate concentrations
Capillary blood samples (25 μl) for blood lactate concentration ([La⁻]) analysis were collected from the ear lobe at the resting period, immediately after the end of each step, and at 3 and 5 min during the recovery period (Lactate Pro, Arkay, Inc, Koyoto Japan).

Data analysis
Prior the VO₂ kinetics modelling, the breath-by-breath collected data were edited to exclude occasional errant breaths caused by swallowing, coughing, sighing or signal interruption and so forth (cf. Fernandes et al. 2012) that typically arise due to some constraints caused by the respiratory snorkel and valve system and by swimming proper characteristics (eg. long apnea moments during the turns). In addition, values greater and lower than ± 4 SD from the local mean were omitted (Özyener et al. 2001). To ensure a true VO₂ steady state, the breath-by-breath data were smoothed at 3 breaths and averaged at 5 s using the time-averaging function of the Cosmed analysis software.

The kinetics of VO₂ was modelled by the following exponential function:

\[
\dot{V}O_2(t) = \dot{V}_b + A_1 \times (1 - e^{-\left(t - T_D_1 / \tau_1\right)}) + A_2 \times (1 - e^{-\left(t - T_D_2 / \tau_2\right)})
\]

Where \( t \) is the time (s), \( \dot{V}_b \) is the VO₂ at the beginning of the exercise (mL.min⁻¹), A1 and A2 are the amplitude of the fast and slow components (mL.min⁻¹), TD₁ and TD₂ are the times of the beginning of the fast and slow components (s) and \( \tau_1 \) and \( \tau_2 \) are the time constants of the fast and slow components (s), respectively. A non-linear regression was applied to fit the time responses of VO₂, using the least square method to obtain the corresponding coefficients (the VO₂ at time is given by the magnitude of the second exponential). The calculation of the VO₂ through the fixed interval method was made by subtracting the average VO₂ observed in the last 40 s of each step of the protocol by the average VO₂ observed in the 3rd min of exercise. All mathematical and modelling procedures were done using the MATLAB R2010b (Mathworks, USA). The individual anaerobic threshold was determined by the [La⁻] / velocity curve modelling method (also using the least square method; Fernandes et al. 2011), being possible to determine the exact point for the beginning of an [La⁻] exponential rise and, therefore, the corresponding step of the incremental protocol.
Statistical analysis

The mean values ± SD for the descriptive analysis were obtained for all the variables of the study and normality of distribution was verified through the Shapiro Wilk test. The T-test for repeated measures was used for the inferential statistics and significant level was established at 0.05. It was considered a (Cohen 1988): (i) small effect size if 0 ≤ |d| ≤ 0.2; (ii) medium effect size if 0.2 ≤ |d| ≤ 0.5; and (iii) large effect size if |d| > 0.5.

Results

Figure 1 shows the VO\textsubscript{2} kinetics of a representative swimmer in the 5, 6 and 7th steps of the intermittent incremental protocol, being evident the appearance of the VO\textsubscript{2SC} superimposed on the primary component.

Figure 1  Oxygen uptake kinetics in the 5, 6 and 7th steps of the incremental protocol in a representative swimmer, being identified the amplitude of the VO\textsubscript{2} slow component (A2)

Complementarily, Table 1 shows the mean ± SD values for the VO\textsubscript{2SC} and other related parameters (obtained through mathematical modelling and from rigid interval methods) in the seven steps of the front crawl incremental intermittent protocol ([La] values were also presented). The most relevant finding was the significant VO\textsubscript{2SC} values found in the three last steps of the protocol (from the 5 until the 7th step), i.e., at intensities higher than the anaerobic threshold (that occurred, generally, at the 4th step). In addition, it was observed that VO\textsubscript{2SC} mean values were higher using the mathematical modelling compared with the fixed interval method in each step of the incremental protocol (P < 0.05; d > 0.76).

Table 1  Mean ± SD values of the VO\textsubscript{2} kinetics parameters extracted from the multi-exponential model and rigid interval method in each step of the incremental protocol. Blood lactate concentrations were also displayed

<table>
<thead>
<tr>
<th>Step</th>
<th>1st step</th>
<th>2nd step</th>
<th>3rd step</th>
<th>4th step</th>
<th>5th step</th>
<th>6th step</th>
<th>7th step</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 (ml.min\textsuperscript{-1})</td>
<td>1874.7±251</td>
<td>1941.4±311</td>
<td>2185.9±207</td>
<td>2260.1±244</td>
<td>2445.3±229</td>
<td>2749.1±385</td>
<td>3082.5±445</td>
</tr>
<tr>
<td>A2 (ml.min\textsuperscript{-1})</td>
<td>4.4±7.4</td>
<td>9.9±17.6</td>
<td>11.8±22.3</td>
<td>9.9±66.6</td>
<td>234.9±29.6*</td>
<td>274.17±103.7*</td>
<td>400.8±11.7*</td>
</tr>
<tr>
<td>TD1 (s)</td>
<td>13.4±4.3</td>
<td>15.6±4.6</td>
<td>17.3±5.4</td>
<td>12.9±5.3</td>
<td>14.2±5.2</td>
<td>13.1±4.1</td>
<td>12.1±4.2</td>
</tr>
<tr>
<td>t1 (s)</td>
<td>25.6±8.0</td>
<td>25.9±5.4</td>
<td>26.2±5.9</td>
<td>30.0±9.9</td>
<td>24.8±8.4</td>
<td>22.3±8.3</td>
<td>23.3±16.1</td>
</tr>
<tr>
<td>TD2 (s)</td>
<td>146±49.1</td>
<td>175±22.6</td>
<td>151±40.5</td>
<td>176±34.1</td>
<td>169±37.3</td>
<td>168±34.2</td>
<td>157±32.7</td>
</tr>
<tr>
<td>t2 (s)</td>
<td>274±17.4</td>
<td>280±14.2</td>
<td>268±48.5</td>
<td>266±54.1</td>
<td>274±33.6</td>
<td>262±43.6</td>
<td>210±47.1</td>
</tr>
<tr>
<td>(\Delta)VO\textsubscript{2SC} (ml.min\textsuperscript{-1})</td>
<td>2.8±9.2</td>
<td>6.4±13.1</td>
<td>13.3±6.2</td>
<td>94.1±49.9</td>
<td>205.1±133.3</td>
<td>239±32.9</td>
<td>301±77.1</td>
</tr>
<tr>
<td>[La] (mmol.l\textsuperscript{-1})</td>
<td>1.15±0.4</td>
<td>1.83±1.22</td>
<td>2.23±1.41</td>
<td>2.56±1.62</td>
<td>3.12±1.31</td>
<td>7.13±1.14</td>
<td>8.41±1.54</td>
</tr>
</tbody>
</table>

A1: amplitude of the 1st exponential (fast component); A2: amplitude of the 2nd exponential (slow component, given by the mathematical modelling); t1 and t2: time constant of the equation for the 1st and 2nd exponentials, respectively; TD1 and TD2 time delay of the 1st and 2nd exponentials, respectively; \(\Delta\)VO\textsubscript{2SC}: slow component given by the fixed interval method, subtracting the average VO\textsubscript{2} observed in the last 40 s of each step of the protocol by the average VO\textsubscript{2} observed in the 3rd min of exercise; [La]: blood lactate concentrations. *Differences between the slow component determined by the mathematical modelling and slow component determined by the fixed interval method; P < 0.05.
Discussion

The aim of this study was to analyse the VO$_{2SC}$ values of well-trained swimmers when performing an incremental protocol from low to severe front crawl swimming intensities. A comparison between mathematical and fixed interval methods for VO$_{2SC}$ assessment was also accomplished. We hypothesised that VO$_{2SC}$ would appear at swimming intensities above the individual anaerobic threshold, i.e., at the heavy and severe intensity domains. The experience was conducted in ecologic swimming pool conditions, using a recently developed and comfortable snorkel and valve system specific for breath-by-breath analysis (Baldari et al. 2013). The main finding of the current study was that, independently of the methodology of assessment used, the VO$_{2SC}$ was evident and had physiological meaning at swimming intensities above the one corresponding to the anaerobic threshold, confirming the initial hypothesis.

Traditionally, the VO$_2$ kinetics response to exercise has been studied at three intensity domains: moderate—below the anaerobic threshold, heavy—above the anaerobic threshold and below the critical power and severe—above the critical power until the VO$_{2max}$ boundary (Burnley and Jones 2007). At intensities above the anaerobic threshold, the VO$_2$ steady state is delayed due to the existence of a VO$_{2SC}$ (Jones and Burnley 2009). In the current study, at intensities above the anaerobic threshold (at the heavy and severe intensity domains), the VO$_{2SC}$ phenomenon was observed (physiological meaning, ≥200 mL.min$^{-1}$), which corroborates the swimming literature where the VO$_{2SC}$ has been reported at intensities higher than the anaerobic threshold (Demarie et al. 2001; Fernandes et al. 2008; Sousa et al. 2011), although this phenomenon was not yet investigated in an entire incremental protocol using mathematical modelling. The reason for the existence of a VO$_2$ slow component is still a matter of debate, but it has been suggested that it is influenced by muscle perfusion pressure and O$_2$ availability (Jones and Poole 2005). In the current study, the use of an incremental protocol that comprises low to severe swimming intensities, reflecting in a progressive increase of the [La$^-$] values, could explain the significant VO$_{2SC}$ values observed.

Although the VO$_{2SC}$ phenomenon was observed using both assessment methodologies, the mathematical modelling method evidenced higher VO$_{2SC}$ values comparing to the rigid interval in agreement with Reis et al. (2013) for submaximal swimming intensities. In fact, Jones and Poole (2005) stated that the later method is a a simple rough estimate of the VO$_2$ slow component. Moreover, when applying the mathematical modelling to front crawl swimming at the intensity corresponding to maximal oxygen uptake, Fernandes et al. (2008) showed a VO$_{2SC}$ of 365.27 mL.min$^{-1}$, a value near that obtained in the current study for the step where the VO$_2$max occurred (the last one). In addition, our results obtained with the fixed interval method were similar to previous studies conducted with the same methodological approach (Demarie et al. 2001; Fernandes et al. 2003).

It seems also important to underline that the values of [La$^-$] corresponding to the anaerobic threshold where lower than the average value of 4 mmol.l$^{-1}$ traditionally used for aerobic capacity training control. This evidences the importance of using individualised methodologies for the characterisation of this boundary, in line with the suggestions of Stegman et al. (1981) and our own data (e.g. Fernandes et al. 2010; Fernandes et al. 2011; Figueiredo et al. 2013). The [La$^-$] values in the final of incremental protocols that aims to assess maximal VO$_2$ values should be around to 8 mmol.l$^{-1}$ (Fernandes et al. 2008; Ogita et al. 1992) that was observed in the current study.

Conclusion

Our results indicated that well trained front crawl swimmers have an evident VO$_{2SC}$ at exercise intensities above the anaerobic threshold. This means that at heavy and severe swimming intensities, the higher work rates leded to the recruitment of faster but more fatigable fibers (type Ila and b), which could lead to less efficient processes, and consequently to higher VO$_{2SC}$ mean values. Our results indicated also that mathematical modelling of the VO$_2$ kinetics along an incremental swimming reveals higher VO$_{2SC}$ as compared to fixed interval methods nonetheless that both methodologies evidences VO$_{2SC}$ values above the typical threshold reported as having a physiological meaning (≥200...
mL.min\(^{-1}\)). So, the VO\(_{\text{SC}}\) should be well considered when performing at intensities above the anaerobic threshold even if the exercise lengths are not too long (as 300 m steps).

**Acknowledgments**

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**References**


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Does back crawl require greater energy expenditure than front crawl at equivalent sub-aerobic threshold speed?

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Keywords: energy cost, stroke frequency, stroke length, front crawl, back crawl

The purpose of this study was to determine the intra-individual differences of energy expenditure between front crawl and back crawl at the same speed below the anaerobic threshold. Seven male swimmers performed 300m front crawl and back crawl at 95 percent of back crawl anaerobic threshold speed. During the trial each swimmer's respiratory gas was analysed using a portable gas analysis system. The speed of each swimmer was controlled by a visual light pacer, and each trial was recorded by a digital video camera. Energy expenditure during the trial was assumed to be equal to the swimmer's oxygen consumption. Stroke frequency and stroke length of the swimmer were calculated from the video image. Energy expenditure in back crawl was significantly higher than front crawl (mlO2/kg/min, front crawl: 38.91±3.13, back crawl: 48.20±5.31). However, there was no difference in stroke frequency (cycle/sec, front crawl: 0.43±0.04, back crawl: 0.43±0.04) and stroke length (m/cycle, front crawl: 2.53±0.17, back crawl: 2.53±0.22) between the two. The results suggested that the superiority of front crawl over back crawl at aerobic intensity is due to the difference of the economy between them, rather than the differences between stroke parameters.

Introduction

Several differences in energy expenditure and stroke parameters between front crawl and back crawl have been reported. Barbosa et al. (3) compared five back crawl swimmers and twelve front crawl swimmers and found front crawl is more economical than back crawl at speeds over 1.4 m/s. Alves et al. (1) compared the energy expenditure of front crawl and back crawl and concluded the difference of the energy expenditure between the two became larger as the swimming speed increased. Hellard et al. (10) compared swimming speed (V), stroke length (SL), and stroke frequency (SF) at races between front crawl and back crawl. They found significant differences in V and SF, but not in SL. However Barbosa et al. and Hellard et al. compared different participant groups and so the individual differences might have affected the results. Also comparison of back and front crawl at the same speed has not been conducted. Alves et al. measured inter-individual differences between front crawl and back crawl. In that study the VO2 values were used as measures of energy expenditure. However, it was not clear whether the trials were conducted at an intensity which requires only aerobic energy resources. To investigate energy expenditure using VO2 values, it is preferable to compare energy expenditure at intensities below anaerobic threshold (AnT) so that anaerobic energy sources do not affect the results. There have been many studies in which anaerobic energy expenditure has been calculated using blood lactate values (3, 4, 5, 8).
However, the individual variation in the relationship between energy expenditure and blood lactate affects the accuracy and reliability of the results (14). Further, blood lactate can severely underestimate muscle lactate concentrations (12).

In summary, to investigate certain differences between front crawl and back crawl, it is necessary to measure the energy expenditure under AnT intensity, and to compare the energy expenditure and stroke parameters between the same participants. Thus the purpose of this study was to determine the intra-individual differences of energy expenditure between front crawl and back crawl at the same speed below the anaerobic threshold.

**Method**

Seven Portuguese male swimmers volunteered their participation (two front crawl swimmers, two back crawl swimmers, two individual medley swimmers, and one breast stroke swimmer). Prior to the energy expenditure measurement, individual AnT speeds for back crawl (vAnt-BC) were determined using a 7*200m incremental test in accordance with Fernandes et al. (6). The first step of the incremental was set at 0.3m/s below the average speed of 400m maximum performance, and the speed was increased by 0.05 m/s for each step. Swimmer’s speed was controlled by a visual light pacer (Pacer 2 swim, KulzerTEC, Santa Maria Feira, Portugal). Blood samples were collected from each swimmer’s fingertip before and after each step, and analysed by a lactate analyser (Lactate Pro, Arkay, Inc, Kyoto, Japan) to measure blood lactate value. AnT was assumed to be the same point as Lactate threshold (LT), and LT was determined as an inflection point of the lactate-velocity curve by lactate-velocity curve modelling (6, 7). A 7*200 test for front crawl was also conducted to investigate the difference of AnT between front crawl and back crawl.

To measure the energy expenditure for front crawl and back crawl at the same speed, two 300m trails (one for front crawl, another for back crawl) at 95 percent of vAnt-BC were conducted with 24 hours rest between each trial. Participants were fitted with a respiratory snorkel (AquaTrainer ®, Kosmed, Rome, Italy) which was connected to a portable gas analyser (K4b2, Kosmed, Rome, Italy). Swimming speed was controlled by a visual light pacer. VO2 values were measured breath by breath, and the measured VO2 was averaged every five seconds (9, 13). Swimmer’s VO2 value was divided by their body mass and expressed as the unit of mlO2/kg/min. Energy expenditure was calculated by averaging VO2 values in the last 30 seconds of the trial. Lactate values after the trial were also measured using the same method as the incremental test to check that the exercise intensity did not exceed AnT level.

The energy expenditure measurement was recorded by a digital video camera (HDR-CX160E, Sony, Tokyo, Japan) to measure SF of the swimmer. The sampling frequency of the camera was 50 Hz, and the electronic shutter speed was 1/120 seconds. SF of the swimmer was calculated by the following equation:

\[
SF \ (\text{cycle/sec}) = 50/FN \quad (\text{Eq. 1})
\]

where FN was the number of the video frames, recorded at 50 frames per second, the swimmer needed to complete one stroke cycle. A stroke cycle was defined as the instant of the entry of the fingertip into the water to the point of the next entry of the same fingertip into the water. SL (m/stroke) was calculated by dividing swimming speed (m/sec) by SF. The swimming speed was assumed to be equal to the speed programmed in the visual light pacer.

Energy expenditure per one stroke (E_stroke: mlO2/kg/cycle) was also calculated by the following equation.

\[
E_{\text{stroke}} = E/(60*SF) \quad (\text{Eq.2})
\]
in which $E$ is the average of VO2 values in the last 30 seconds of the trial. Since the unit of the energy expenditure is (mlO2/kg/min), the energy expenditure values were divided into SF which was expressed as (cycle/min) by multiplying 60 to the original SF values (cycle/sec) to get $E_{stroke}$.

The intra-individual difference in Energy expenditure SF, SL, and $E_{stroke}$ between front crawl and back crawl were evaluated by paired t-tests.

**Results**

Table 1 and Table 2 show the outcomes from 7*200m tests for front crawl and back crawl. Table 1 shows speeds and lactate values at each step of the 7*200m tests and at LT (AnT) in front crawl and back crawl. There was significant difference in LT speeds between front crawl and back crawl (m/s, front crawl: 1.23±0.04, back crawl: 1.13±0.03). However there was no significant difference in lactate values (front crawl: 3.51±0.52, back crawl: 3.43±0.43). Table 2 shows 95 percent of vAnT-BC (testing speeds in the 300m trials for both front crawl and back crawl) for each swimmer. The speeds corresponded to 87.62±3.90% of anaerobic threshold speeds in front crawl.

**Table 1** Speeds and lactate values at each step of the 7*200 tests and at LT (AnT)

<table>
<thead>
<tr>
<th>Step</th>
<th>speed (m/s)</th>
<th>lactate (mmol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>0.97±0.05</td>
<td>2.26±0.72</td>
</tr>
<tr>
<td></td>
<td>1.02±0.05</td>
<td>2.40±0.88</td>
</tr>
<tr>
<td></td>
<td>1.07±0.05</td>
<td>2.94±1.12</td>
</tr>
<tr>
<td></td>
<td>1.12±0.05</td>
<td>3.91±2.03</td>
</tr>
<tr>
<td></td>
<td>1.16±0.03</td>
<td>4.99±2.41</td>
</tr>
<tr>
<td></td>
<td>1.20±0.03</td>
<td>6.10±1.23</td>
</tr>
<tr>
<td></td>
<td>1.24±0.03</td>
<td>8.82±1.22</td>
</tr>
<tr>
<td></td>
<td>1.13±0.03</td>
<td>3.43±0.43</td>
</tr>
<tr>
<td>**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FC</td>
<td>1.15±0.04</td>
<td>3.07±0.44</td>
</tr>
<tr>
<td></td>
<td>1.18±0.04</td>
<td>3.14±0.40</td>
</tr>
<tr>
<td></td>
<td>1.23±0.04</td>
<td>3.53±0.65</td>
</tr>
<tr>
<td></td>
<td>1.28±0.04</td>
<td>4.61±0.51</td>
</tr>
<tr>
<td></td>
<td>1.33±0.04</td>
<td>5.93±1.21</td>
</tr>
<tr>
<td></td>
<td>1.38±0.04</td>
<td>7.79±1.46</td>
</tr>
<tr>
<td></td>
<td>1.39±0.04</td>
<td>10.25±2.07</td>
</tr>
<tr>
<td></td>
<td>1.23±0.04</td>
<td>3.51±0.52</td>
</tr>
<tr>
<td>**</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2** 95% of vAnT-BC for each swimmer

<table>
<thead>
<tr>
<th>Participants</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>AVE± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (m/s)</td>
<td>1.08</td>
<td>1.06</td>
<td>1.05</td>
<td>1.06</td>
<td>1.11</td>
<td>1.14</td>
<td>1.05</td>
<td>1.08± 0.03</td>
</tr>
<tr>
<td>Percentage</td>
<td>83.36</td>
<td>82.28</td>
<td>92.45</td>
<td>90.24</td>
<td>87.06</td>
<td>87.58</td>
<td>90.37</td>
<td>87.62± 3.90</td>
</tr>
</tbody>
</table>

Table 3 shows that the lactate values after the 300m tests. In both front crawl and back crawl, lactate values were significantly lower than AnT lactate values. There were significant differences (p<.01) in energy expenditure and $E_{stroke}$ between front crawl and back crawl (Figure 1). There was no significant differences in SF (cycle/sec) and SL (m/cycle) between front crawl (SF: 0.43±0.04, SL: 2.53±0.17) and back crawl (SF: 0.43±0.04, SL: 2.53±0.22).

**Table 3** Lactate value (mmol) after each 300m test

<table>
<thead>
<tr>
<th>Participants</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>AVE± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>300BC-post</td>
<td>2.0</td>
<td>1.8</td>
<td>2.6</td>
<td>2.2</td>
<td>3.1</td>
<td>3.0</td>
<td>1.9</td>
<td>2.4±0.53**</td>
</tr>
<tr>
<td>300FC-post</td>
<td>2.0</td>
<td>2.0</td>
<td>2.6</td>
<td>2.2</td>
<td>2.0</td>
<td>3.2</td>
<td>1.6</td>
<td>2.2±0.52**</td>
</tr>
</tbody>
</table>

**significant difference from LT value (p<.01)**
Discussion

The main findings in this study were that front crawl showed smaller energy expenditure and lower relative intensity than back crawl in the same speed, whereas stroke length and stroke frequency were almost the same.

Since the lactate values after the 300m tests were significantly lower than lactate values at LT, it was clear that the testing intensity was below the anaerobic threshold.

In this study, front crawl showed smaller energy expenditure than back crawl at the same speed. This was due to the fact that the relative intensity was different between front crawl and back crawl (front crawl: approximately 87% of AnT speed, back crawl: 95% of AnT speed) even though the swimming speed was the same. This result indicated that front crawl was more economical than back crawl.

Although Alves et al. (1) showed small energy expenditure difference at slow speeds between front crawl and back crawl, this study showed relatively large difference. However, Alves’s study might contain some errors in the result because of the testing speed. In this study, the average vAnT in back crawl was 1.13 m/s, while the testing speed in Alves’s study ranged from 1.1 m/s to 1.4 m/s, which is much higher than this study. Thus, it is possible that those speeds in Alves’s study exceeded AnT level, therefore anaerobic energy sources affected the results. In this study it was found also that the energy swimmers expend to complete one stroke cycle was much higher in back crawl than in front crawl. In other words, front crawl is more economical than back crawl at the same sub AnT speed.

Despite the fact that front crawl is typically swum at higher SF than back crawl in competitions (10, 11), front crawl and back crawl showed almost the same SF and SL in this study. This result indicates that the basic stroke parameters of front crawl and back crawl are almost the same when swum at the same speed.

To understand why front crawl is more economical than back crawl although the stroke parameters are quite similar, further investigation will be needed to discover the difference of force application, intra-cycle velocity fluctuation, and detailed hand kinematics during a stroke cycle between the two.

Conclusion

At speeds just under back crawl anaerobic threshold speed, there is no difference in stroke parameters between front crawl and back crawl. However front crawl is more economical than back
crawl because the energy required for completing one stroke cycle in back crawl is greater than in front crawl.

References
Ventilatory, metabolic and kinematic responses in sprint versus distance swimmers

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Abstract

The aim of this study was to compare the speed, oxygen uptake (\(\dot{V}\)O\(_2\), consumption), blood lactate concentration ([La]b), and stroke rate (SR) in sprint and middle-distance swimmers. Seven male elite middle-distance swimmers (performance level=89% of the world record) and seven male sprint swimmers (performance level=88% of the world record) were recruited. Ventilatory, metabolic and kinematic parameters were obtained during a 6 x 300-m incremental swimming exercise to exhaustion. \(\dot{V}\)O\(_2\) kinetics were compared between groups using a 500-m interval training set (IT-500) swum at the lactate threshold (LT). Speed at \(\dot{V}\)O\(_2\)\(_{\text{max}}\) was faster for the middle-distance swimmers (1.51 ± 0.02 m.s\(^{-1}\)) than the sprinters (1.34 ± 0.07 m.s\(^{-1}\)). Speed at LT was also faster for the middle-distance swimmers (3.1 ± 1.2 mmol.L\(^{-1}\); v LT = 1.46 ± 0.01 m.s\(^{-1}\), equivalent to 96.7 ± 0.5% of v \(\dot{V}\)O\(_2\)\(_{\text{max}}\) than the sprinters (4.5 ± 1.5 mmol.L\(^{-1}\); v LT = 1.22 ± 0.06 m.s\(^{-1}\), 91 ± 1.9% of v \(\dot{V}\)O\(_2\)\(_{\text{max}}\); P < 0.01). The middle-distance swimmers had a higher stroke rate at LT (36.7 ± 4.5 vs. 30.3 ± 0.7 s.min\(^{-1}\)) and consumed a larger \(\dot{V}\)O\(_2\)\(_{\text{max}}\) fraction (95 ± 2 vs. 84 ± 5% of \(\dot{V}\)O\(_2\)\(_{\text{max}}\); P < 0.01). A significant positive correlation was observed between \(\Delta\dot{V}\)E and \(\Delta\)SR (\(r^2 = 0.93, P < 0.01\)) in the middle-distance swimmers during the IT-500, whereas a negative relationship was observed with \(\Delta\)stroke length (\(r^2 = 0.81, P < 0.01\)). The middle-distance swimmers were typically 10-15% faster at the lactate threshold and at the maximal oxygen uptake. In contrast, the blood lactate concentration was 40% higher in the sprint swimmers but the stroke rate was 15% lower at the lactate threshold.

Introduction

The metabolic processes mobilised in competition differ greatly with the swimming distance (Rodriguez & Mader 2009). By simulating the energy share during maximal swimming, these authors showed the relative contributions from the three metabolic processes (i.e., the phosphagen, glycolytic and aerobic systems) to be 20, 39 and 41% for 100-m swum in 48 s by sprinters and 3, 11 and 86% for 1500-m swum in 14 min 50 s.

In the 100-m event, the glycolytic and aerobic energy delivery systems are rapidly and completely activated (Rodriguez & Mader 2009; Olbrecht 2009). Muscle lactate accumulates quickly, causing acidosis (reduced pH) and the progressive inhibition of glycolysis. This in turns contributes to a decline in the rhythm and power of muscle contractions, which are inversely proportional to the energy delivery capacity of the aerobic system (Rodriguez & Mader 2009; Olbrecht 2009). The high correlations between \(\dot{V}\)O\(_2\)\(_{\text{max}}\) and 100-m performance (\(r=0.79\)) indicate that the aerobic pathway is implicated at several levels in the 100-m event. In swimming as in many endurance sports (middle-distance running, cross-country skiing, cycling), it has been suggested that training at the lactate threshold (LT) is essential for high-level endurance performance (Lucia et al. 1998; Mahood et al. 2001; Joyner & Coyle 2008). Most of these studies have emphasised the high velocities reached by elite athletes at the LT, expressed in percentage of the velocity at maximal oxygen uptake (v \(\dot{V}\)O\(_2\)\(_{\text{max}}\)), and their capacity to perform prolonged exercise at heavy workloads, about 90% of maximal oxygen uptake (\(\dot{V}\)O\(_2\)\(_{\text{max}}\)) (Lucia et al. 1998; Mahood et al. 2001; Joyner & Coyle 2008).
For heavy, constant-load exercise above the LT, the slow component of \( \dot{V}O_2 \) has been defined as the delayed steady state that is higher than the \( \dot{V}O_2 \) requirement estimated by extrapolating the relationship between \( \dot{V}O_2 \) and the work rate for moderate exercise (Carter et al. 2000; Gaesser & Poole 1996). Other studies conducted on populations of sedentary subjects (Aaron et al. 1992; Gaesser & Poole 1996) and Olympic level cyclists (Lucia et al. 1998) have observed the \( \dot{V}O_2 \) slow component during exercise at constant workload at a velocity close to the LT. Recently, Pessoa et al. (2011) demonstrated the slow component of \( \dot{V}O_2 \) in nine well-trained male swimmers at speeds slightly lower than those at the respiratory compensation point. The characteristics of the slow component of \( \dot{V}O_2 \) (i.e., amplitude, delay and kinetics) depend on the absolute exercise intensity, as \( \dot{V}O_2 \) is mainly regulated by the splitting of ATP and phosphocreatine (Carter et al. 2000; Gaesser & Poole 1996). The appearance of the slow \( \dot{V}O_2 \) component is mainly due to the recruitment of type II fast fibers with fatigue. These fibers have a phosphate to oxygen ratio that is 18% lower than in type I fibers and, therefore, more oxygen is required to produce the same level of ATP turnover and thus sustain a given power output. Another factor leading to the slow component appearance is the increase in cardiac and ventilatory work. The bioenergetic and muscle differences in long-distance and sprint swimmers probably account for the differences in the kinetics of oxygen consumption.

For the same relative exercise intensity, the energy demand pattern may also differ with the biomechanical constraints of the activity. For example, Billat (2000) reported that triathletes did not express the \( \dot{V}O_2 \) slow component while running as compared with cycling even though they had the same endurance times in these two types of exercise (at 90% of the power or velocity associated with \( \dot{V}O_2\max \)). From this perspective, swimming, an activity characterised by high technical and biomechanical constraints and a low yield, may display differences in evolution depending on the technique and swimming specialty. For instance, for front crawl swimming at submaximal intensities, Demarie et al. (2001) suggested that an increase in ventilation would partly explain the \( \dot{V}O_2 \) slow component and the changes in stroking parameters. In long-interval or continuous swim training, for example, muscle fatigue progressively diminishes stroke cycle efficiency, which in turn is compensated by an increase in movement frequency in an attempt to maintain the swim velocity (Toussaint & Beek 1992; Zamparo et al. 2005). This increase in movement frequency may then cause a further increase in the ventilatory parameters, leading to a continuous deterioration in stroke efficiency.

These works suggest that the physiological differences between middle-distance and sprint swimmers (i.e., muscle metabolism and cardiovascular capacities for oxygen transport) will manifest as specific ventilatory and technical responses. The objective of this work was to compare these responses at swimming speeds at the LT and at \( \dot{V}O_2\max \).

**Population and methods**

**Subjects.** Seven male distance swimmers (21.4 ± 3.5 yr; 71 ± 5 kg; 180 ± 5 cm) and seven sprinters (20.5 ± 4.1 yr; 80 ± 10 kg; 186 ± 6 cm) competing at the national and international levels were selected to participate in this study. The study was reviewed and approved by the local University Committee on Human Research and written informed consent was obtained from each participant.

**Experimental design.** All participants completed two experimental sessions in a 50-m open pool (26°C) during one week of standardised training. The first test consisted of a progressive incremental test to exhaustion to determine the lactate threshold and maximal oxygen uptake. The second test was the 500-m (IT-500) swum at the speed corresponding to the individual LT.

**Equipment.** Swimming speed was monitored using an Aquapacer ‘Solo’ (Challenge and Response, Inverurie, UK) so that each swimmer could match auditory signals with visual markers positioned every 12.5 m along the edge of the pool. Blood lactate concentrations ([La]b, expressed in mmol.L\(^{-1}\)) were determined from a fingertip blood sample using a portable lactate analyzer (Lactate Pro, Arkray,
Breath-by-breath respiratory data were collected with a portable gas analyzer (Cosmed K4b², Rome, Italy) connected to an Aquatrainner snorkel (Cosmed, Rome, Italy). Heart rate (HR) was recorded through the K4b² device using a Polar belt system (Polar Electro, Kempele, Finland). Mean SR (stroke.min⁻¹) was measured in a 25-m central zone using a base 3 chronometer (Seiko, base 3, Japan).

Incremental test. The subjects swam six consecutive 300-m blocks separated by 30-s resting intervals. The starts were performed from the pool wall, and because they were breathing in the snorkel, the swimmers were asked to make hand turns rather than tumble turns. Individual personal best 400-m freestyle performances recorded within the month preceding the testing period were used to determine the pace of the incremental stages. The pace of the first 300-m was 30 s slower than the time required to swim 300-m at the adjusted 400-m pace. This time was then reduced by 5 seconds for each consecutive 300-m until the final 300-m. Swimmers were verbally encouraged to reach their maximal speed during the final 300-m.

The breath-by-breath values were averaged over 15 s. VO₂peak was defined as the highest 15-s average value recorded during the incremental test. Its corresponding velocity (V VO₂peak) was defined as the slowest velocity at which VO₂peak was reached, according to a method defined elsewhere (Borrani et al. 2001). Blood lactate concentration was measured at the end of each 300-m, and the lactate threshold was determined by two independent observers as the point of the first inflection of the lactate-work rate curve.

Part one: Differences in the physiological and kinematic responses of sprinters and middle-distance swimmers

A 5-min warm-up at 60% of VO₂peak was completed 15 min before each test in order to maintain stable oxygen uptake kinetics. The velocity (m.s⁻¹) was adjusted to take into account the time lost during the hand turns. The [La]b was measured at the end of each IT set. The velocity and SR recorded per length were averaged. The highest 15-s average VO₂ and HR values were defined for the IT-500.

Changes in the parameters throughout the IT-500. The changes in the ventilatory (VO₂, CO₂, VE) and stroking (SR, SL) parameters over the IT-500 were defined as the differences between the period extending from the beginning of the first 500-m block to the onset of the VO₂ slow component, and the period extending from the onset of the VO₂ slow component to the end of the first 500-m block of the IT-500 (ΔVO₂500, ΔCO₂500, ΔVE500, ΔSR500, ΔSL500, respectively) (see, for instance, Bearden & Moffatt 2001, for the rationale of a similar method).

Statistical analysis. The Scheffe test for one-way repeated measures ANOVA was applied to identify differences (1) between the VO₂peak and HRpeak values recorded during the incremental test and the IT-500 session and (2) between the several physiological and stroking responses recorded in the sprinters and the middle-distance swimmers. For the IT-500 the changes in stroke rate were linearly related to the changes in ventilatory parameters (ΔVO₂, ΔCO₂, ΔVE).

Results of the 6 x 300-m incremental test. The speeds and maximal ventilatory values for the sprinters and middle-distance swimmers are presented in Table 1. At LT, the middle-distance swimmers swam faster and had higher VO₂ and lower [La]b (1.46 ± 0.01 m.s⁻¹, 60.1 ± 6.4 mL.kg⁻¹.min⁻¹ and 3.1 ± 1.2 mmol.L⁻¹ vs. 1.22 ± 0.06 m.s⁻¹, 46.1 ± 2.4 mL.kg⁻¹.min⁻¹ and 4.5 ± 1.5 mmol.L⁻¹; P < 0.05). The relative values were also higher for the middle-distance swimmers (VO₂ at LT was 95.5 ± 2% of VO₂max and vLT was 97 ± 2% of vVO₂max vs. 84 ± 5% of VO₂max and 91 ± 2% of vVO₂max).
Table I
Maximal physiological variables obtained in the 6 x 300-m incremental test to exhaustion

<table>
<thead>
<tr>
<th>Variables</th>
<th>Middle-distance</th>
<th>Sprinters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V \text{ (m.s}^{-1}\text{)}$</td>
<td>1.51 ± 0.02</td>
<td>1.35 ± 0.08*</td>
</tr>
<tr>
<td>$\dot{V}O_2 \text{ (mL.kg}^{-1}.\text{min}^{-1}\text{)}$</td>
<td>69.2 ± 6.5</td>
<td>55.1 ± 3.5*</td>
</tr>
<tr>
<td>$\dot{V}CO_2 \text{ (mL.kg}^{-1}.\text{min}^{-1}\text{)}$</td>
<td>62.1 ± 5.7</td>
<td>52.2 ± 7.1*</td>
</tr>
<tr>
<td>$\dot{V}L \text{ (mL.kg}^{-1}.\text{min}^{-1}\text{)}$</td>
<td>1749 ± 166</td>
<td>1770 ± 340*</td>
</tr>
<tr>
<td>Lactate (mmol.L$^{-1}$)</td>
<td>6.9 ± 1.4</td>
<td>8.8 ± 1.5*</td>
</tr>
<tr>
<td>RPE (a.u.)</td>
<td>18.4 ± 3.1</td>
<td>18.5 ± 1.5*</td>
</tr>
<tr>
<td>HR (b.min$^{-1}$)</td>
<td>196.0 ± 7.3</td>
<td>194.0 ± 6.9*</td>
</tr>
</tbody>
</table>

Part two: Relationships between the $\dot{V}O_2$ slow component and kinematic responses during the IT-500

For the sprinters, the ventilatory and technical parameters were not significantly modified during the entire set. Conversely, for the middle-distance swimmers, $\dot{V}O_2$ (3998 ± 454 vs. 4351 ± 441 mL.min$^{-1}$, $P < 0.05$), $\dot{V}CO_2$ (3088 ± 614 vs. 3745 ± 379 mL.min$^{-1}$, $P < 0.05$) and $\dot{V}L$ (89.9 ± 8.4 vs. 103.8 ± 15.6 L.min$^{-1}$, $P < 0.05$) increased from the onset of the $\dot{V}O_2$ slow component to the end of the 500-m block. Stroke length (SL) showed a trend toward decrease (2.40 ± 0.13 vs. 2.32 ± 0.15 m.cycles$^{-1}$, $P < 0.05$), while the inverse (but not significant) trend was observed for SR (35.5 ± 3.3 vs. 36.5 ± 3.2 cycles.min$^{-1}$, $P = 0.09$).

$\Delta \dot{V}E$ was positively correlated with $\Delta \dot{SR}$ ($r^2 = 0.93$, $P < 0.01$) and negatively correlated with $\Delta \dot{SL}$ ($r^2 = 0.81$, $P < 0.01$) (Figure 1).

Discussion

Main findings. The main findings were as follows: (1) the middle-distance swimmers were typically 10-15% faster at the lactate threshold and at the maximal oxygen uptake, whereas their blood lactate concentration was 40% higher; (2) all seven middle-distance swimmers and a single sprinter displayed a significant $\dot{V}O_2$ slow component during the IT-500; and (3) the increase in ventilation of the middle-
distance swimmers during the IT-500 was significantly linked to an increase in stroke rate and a decrease in stroke length.

Part one: Differences in ventilatory and metabolic responses of sprinters and middle-distance swimmers

As reported in previous studies, the absolute and relative speeds at the lactate threshold and \( \dot{V}O_2 \) were faster for the swimmers with higher endurance performance. These speeds, which were 16% faster at LT and 11% faster at \( \dot{V}O_2 \text{max} \), were clearly associated with higher energy expenditure because, given that the drag force is related to swimming speed in a cubic relationship, small increments in swimming velocity significantly increase the mechanical power that is required and thus the metabolic power that the swimmer must generate (Rodriguez & Mader 2009). Although their energy expenditure and stroke rate were higher, the middle-distance swimmers showed lower blood lactate values despite the higher \( \dot{V}CO_2 \). This can be interpreted as the predominance of the oxygen uptake and delivery system and a high capacity for lactic acid reoxidation. Indeed, although it was activated in the middle-distance swimmers, glycolysis reached a steady state with the production of high levels of muscle lactate (Olbrecht 2009).

For the sprinters, the low \( \dot{V}O_2 \text{max} \) and the high accumulation of blood lactate at slow speeds compared with their competition speeds was a problem, given the high contribution from the aerobic pathway during 100-m trials (~40%). If the glycolytic power is too high compared with the oxidative processes in muscle, more pyruvate/lactate than can be combusted is produced even at low intensities (Olbrecht 2009). This results in intracellular acidosis and the inhibition of glycolysis, which therefore underestimates the development of oxidative processes (Mader et al. 1983). These results suggest that it might be useful to have sprinters perform exercises that develop both oxidative and glycolytic capacities.

Part two: Relationships between the \( \dot{V}O_2 \) slow component and kinematic responses in middle-distance swimmers

During a swimming bout performed at the lactate threshold speed (determined during a progressive 6 x 300-m incremental test to exhaustion), all seven middle-distance swimmers exhibited a \( \dot{V}O_2 \) slow component that allowed them to reach ~92% \( \dot{V}O_2 \text{peak} \), a blood lactate concentration of 4.1 ± 1.3 mmol.L\(^{-1}\), and a perceived exertion rating of 17.3 ± 2.4, thus reflecting heavy-intensity exercise (Gaesser & Poole 1996).

An original finding was the interaction effects among the increased stroke rate, the decreased stroked length and the augmented ventilation during the course of the exercise. The influence of augmented ventilation on the slow component has been described by others (Aaron et al. 1992; Gaesser & Poole 1996; Carter et al. 2000; Demarie et al. 2001). This augmentation may be related not only to the higher energy cost of respiration at maximal exercise, but also to an increase in the inspiratory breathing resistance, thereby causing an increase in the maximal voluntary ventilation (Carra et al. 2003). Regarding the relationship between movement frequency (stroke rate) and the slow component, several authors (Gaesser & Poole 1996; Pringle et al. 2003) found that the amplitude of the slow component augments with increasing pedaling rate, certainly in relation to a change in motor unit recruitment patterns (need to recruit a faster twitch fiber population at higher cadences). In addition, cyclical locomotion and the inspiration/expiration cycle have reciprocal effects, since respiratory muscle contraction affects the locomotor cycle (Lee & Banzett 1997; Steinacker et al. 1993). In our study, it could be speculated that the coupling of ventilatory and kinematic responses in the IT-500 was dependent on the interaction of chemical, neuromechanical and technical factors. First, the neuromuscular fatigue during the IT-500 could have induced a decline in propulsive efficiency with a progressive increase in the energy cost (Demarie et al. 2001; Toussaint & Beck 1992). This fatigue would then have led to the recruitment of additional motor units or less efficient muscles and a concomitant increase in \( \dot{V}O_2 \) and ventilation (Gaesser & Poole 1996; Carter et al. 2000; Krustrup et al. 2004). On the other hand, the decline in propulsive efficiency might have been related
to changes in swimming technique, such as the decrease in stroke length and the compensatory increase in stroke rate (Zamparo et al. 2005). The cumulative relationships among these factors (neuromuscular fatigue, decrease in propulsive efficiency, increase in energy cost, modification in technique, high energy cost of breathing) may have contributed to the increase in the $\dot{V}O_2$ slow component amplitude and the ventilatory responses, thereby leading to a further increase in movement frequency.

**Conclusion**

The sprint swimmers were 10-15% slower at the lactate threshold and at maximal oxygen uptake for a blood lactate concentration that was 40% higher. These responses suggest the predominance of glycolytic processes at the expense of aerobic processes. Conversely, for the middle-distance swimmers, $vLT$ represented 97% of $\dot{V}O_{2\text{max}}$ and $\dot{V}O_2LT$ represented 95.5% of $\dot{V}O_{2\text{max}}$, confirming that their exceptional aerobic capacities allowed for considerable oxidation of energy substrates and the lactate produced by glycolysis. At these swimming speeds indicating relatively high intensity, the middle-distance swimmers exhibited a large amplitude in the $\dot{V}O_2$ slow component and an increase in the ventilatory response, linked to an increase in stroke rate and a decrease in stroke length.

**References**


**Observation of the soft palate while breathing in a simulated swimming situation**

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**Keywords:** airway change, soft palate, endoscope, pronunciation

**Abstract**

How to control breathing is one of the most difficult things for beginner swimmers. This breathing means to change the airway which may be carried out by the soft palate. Controlling the soft palate is difficult because it is controlled by the autonomic nerves. The purpose of this research is to try to find the intentional way of soft palate control. We observed the motion of the soft palate with an endoscope and at the same time measured oral pressure. In order to change the exhaling route from the nose to the mouth, we found that to pronounce the sound ‘Mnn’ and ‘Pah’ is best way to control the soft palate spontaneously.

**Introduction**

Respiration is one of the important autonomic functions for maintaining homeostasis. Respiration is the only characteristic of autonomic functions that can be intentionally controlled. The breathing function involves inhalation, exhalation and breath holding. In case of swimming, how to control breathing is one of the most difficult things for swimming beginners. We reported that the airway change has been successful in skilled swimmers. In order to prevent swimming apnea, we studied breathing from the viewpoint of airways. Skilled swimmers blow out from the nose when their faces are in the water, and at last, they forced out large volume from their mouths at the moment their faces are rising up from the water surface. Swimmers can vary the exhaling airway from the nose to the mouth. This airway change may be caused by the soft palate. Intentional control of the soft palate is difficult because it is controlled by the autonomic nerves. At the moment of swimming breathing instruction for beginners, most instructors do not point out the airway change, because they are not aware of soft palate motion or do not intend for swimmers to move their soft palate.

The purpose of this research was to describe the soft palate action during airway change of exhalation while swimming. An endoscope was not used in water so we simulated swimming by taking a film in the laboratory.

**Method**

The experienced instructor often advises beginners to say some words while breathing. These words phonate, even though the face is under the water. Making bubbles by the exhaling air saying ‘Mnn’
through the nose, or saying ‘Pah’ or ‘Fah’ through the mouth when the face is breaking the water’s surface in order to blow out strongly. So we employed five patterns to simulate breathing in the laboratory, saying ‘Mnn’ and ‘Pah’ or ‘Fah’ combinations. The difference between ‘Pah’ and ‘Fah’ is the lip position. In saying ‘Pah’, the lips are shut perfectly, so the oral pressure is going high, but in saying ‘Fah’, the lower lip touches the inside of the upper teeth and opens the lips a little. Therefore, the oral pressure is lower in case of ‘Fah’ than ‘Pah’.

From these instructions, we employed following the five patterns of breathing:

1. Closing the mouth with no oral high pressure, then exhaling from the mouth saying ‘Pah’.
2. Closing the mouth with high oral pressure, then exhaling with saying ‘Pah’ from the mouth.
3. Exhaling from the nose with ‘Mnn’, then exhaling from the mouth saying ‘Pah’.
4. Exhaling from the nose with ‘Mnn’, then exhaling from the mouth saying ‘Fah’.
5. Exhaling from the nose with no words, then exhaling from the mouth saying ‘Pah’.

The five male subjects, who voluntarily participated in this study, were healthy university students. Each subject sat on a chair in the laboratory and exhaled using the aforementioned five patterns.

We used the endoscope (V1SERA-OTV-S7Pro, OLYMPUS Co., Japan) for observing the motion of the soft palate while simulating swimming breathing. The endoscope was inserted from the nasal cavity. At the same time, we measured the oral cavity pressure changes using a pressure sensor, which we used before\(^{2,3}\), simultaneously. Images were recorded on a DVD disk and we analyzed the motion synchronised with oral pressure after the experiments. Those data were recorded on LogWorx (Distributed Design Corporation) program.

This experiment was approved by the Kokugakuin University Ethic Committee and we obtained informed consents from the subjects.

**Results**

![Graph showing oral pressure (cmH2O) average of all subjects]

We obtained oral cavity pressure curves in each of the Patterns 1 to 5.

We measured the peak pressures from the pressure curve in each pattern for every subject. Fig.1 shows the average value of all subjects in each pattern.

The endoscope took a picture at the lowest position of the soft palate (Picture 1).
Picture 1  Resting position of the soft palate

Figure 2  The oral pressure curve of Pattern 1(left) and the picture of the soft palate(right) at the highest position of the soft palate

In Fig.2, the sharp-pointed peaks were at the moments of saying ‘Pah’, then inhaling from the mouth above the water surface. The right picture shows the position of the soft palate at the peak of oral pressure.

Figure 3  The oral pressure curve of Pattern 2(left) and the picture of the soft palate(right)

In Fig.3, the lips are closed and cheeks expanded, so the curve was going up before saying ‘Pah’. And the image shows the high position of the soft palate before saying ‘Pah’.

Figure 4  The oral pressure curve of Pattern3(left) and the picture of the soft palate(right)

Fig.4 shows the exhalation from the nose while saying ‘Mnn’, so oral pressure was not going up and the soft palate is going up when saying ‘Pah’ with the peak of the curve.
Fig. 5 shows exhaling from the nose with 'Mnn', then exhaling from the mouth saying ‘Fah’. The soft palate rises about half that of ‘Pah’.

The oral pressure is not rising high, because subjects are exhaling from the nose, then exhaling from the mouth saying ‘Pah’.

**Discussion**

Picture 2(left) shows the lower position of the soft palate while saying ‘Mnn’ in Pattern 3 same as Pattern 4.

The highest oral pressure was Pattern 2 (Fig. 3), at the same time, the soft palate moved to the highest position saying ‘Pah’.

**Picture 2** The position of the soft palate when pronouncing ‘Mnn’
When a swimmer breaths in in breaststroke, they start exhalation from the nose while our faces are in underwater(Position A). As face is rising up, exhalation pressure is falling down. At the point that the nasal cavity comes out from the surface of the water (Position B), we recognise the surface and change the airway of exhalation to the mouth. Tsubone reported that the flow volume sensor in the nose is more sensitive than that in the mouth. The nasality speech sounds were induced by the soft palate control in order to exhale from nose. The change of the airway for ventilating large volume is reasonable from this report, that the sensor in the nose would be sensitive. The large volume of exhalation is needed for blowing out the water over the mouth, while falling down from the face (Position C). Also, fast ventilation is requested for swimming skill.

Another point is flexibility of the soft palate. In case of high oral pressure, the soft palate might be hard to move. This means airway change is not easy for beginners in high tension around the pharynx. Moreover, exhalation from the mouth is easy for inhalation from the mouth,because swimmer need not change one's air way.

In swimming instruction especially for children and beginners, breathing skill is very important. One of the important breathing skills is airway change from the nose to the mouth. These airway changes might be controlled by the soft palate, which are controlled by the autonomic nervous system. Usually those autonomic functions are difficult to control intentionally. But pronouncing ‘Mnn’ and ‘Pah’ induces intentional action of the soft palate, so using these pronunciations might be effective for swimming breathing.

**Conclusion**

From the results of observation about the soft palate,

- To recognise the water surface, exhaling from the nose might be effective.
- Pronouncing ‘Mnn’ makes an airway from nose.
- Saying ‘Pah’ induces the soft palate action to change the airway from the nose to the mouth.
• After saying ‘Pah’ it might be good to inhale a large volume from the mouth.

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Bioelectrical impedance vector migration induced by training in young competitive synchronised swimmers
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Keywords: synchronised swimming, BIA, body composition, hydration, fluids, dehydration

Abstract
Introduction. A synchronised swimming (SS) training session typically includes specific drills, choreographies, and physical conditioning exercises, imposing complex physiological demands (Rodriguez-Zamora et al. 2012). Training volume and intensity differs depending on the age and competitive level of the swimmers. Bioelectrical impedance vector analysis (BIVA) is a non-invasive and safe technique for assessing hydration and body composition changes (Lukaski & Piccoli 2012). This study applied BIVA to the assessment of hydration changes evoked by SS during a typical training session in swimmers of different age and competitive level.

Method. 59 swimmers were divided into 1) juniors (JR) (16.7±0.9 years) and pre-juniors (pre-JR) (13.9±0.9 years). Body height (h) and mass (BM) were assessed following the norms and procedures of the ISAK. BIVA was conducted PRE and POST a typical training session (pre-JR 2.5±0.1 h; JR 4.0±0.2 h). A multi-frequency wrist-to-ankle BIA meter device (Z-Metrix, BioparHom, France) was used and 50 kHz whole-body BIA vectors were analysed by the resistance (R) – reactance (Xc) graphic method, and Z mean values plotted (Piccoli et al. 1994). PRE-POST differences were tested by paired t-test. Hotelling’s T² test determined differences in the complex localised vector through the 95% confidence and tolerance intervals.

Results. Significant differences were found in whole-body BIA vector in both pre-JR ($T^2$=25.6, $p=0.003$) and JR ($T^2$=25.8, $p=0.001$). Changes were observed between PRE and POST in BM (pre-JR: 47.0±7.2 kg vs. 46.7±7.3 kg, $p<0.001$); JR: 53.7±4.9 kg vs. 53.4±4.9 kg, $p<0.001$), R (pre-JR: 530±46 Ω vs. 548±45 Ω, $p<0.001$); JR: 503±33 Ω vs. 524±45 Ω, $p=0.004$), and Xc (pre-JR: 64.4±5.4 Ω vs. 66.6±4.8 Ω, $p=0.002$);
JR: 66.0±2.9 Ω vs. 70.3±4.3 Ω, P<0.001). BIVA showed significant vector migration from PRE to POST (T²=8.99; p<0.05) in JR, whereas no changes were noted in pre-JR (T²=1.92; P>0.05).

Conclusions. Both JR and pre-JR swimmers showed a migration of the BIA vector characterised by an increase in length (R) and height (Xc), likely as a result of moderate dehydration. Regardless of age and competitive level, a typical SS training session affects the homeostatic hydration level of the swimmers. BIVA analysis appears to be sensitive enough to detect these changes (mean differences: 0.5–0.8% BM). These preliminary results should be considered by coaches, nutritionists, and physicians in order to ensure adequate fluid intake during training.

Introduction
Synchronised swimming (SS) enjoys worldwide popularity and has been part of the Olympic program since 1984. This highly technical sport, combines aerobic and anaerobic fitness, endurance, flexibility, strength, power, acrobatic and performance skills, and choreography requiring long hours of training to attain such broad attributes (Mountjoy 2009). The young female swimmers often start recreationally and may enter high-level competition at a young age, around 13–15 years, similarly to other aesthetic sports such as gymnastics (Mountjoy 1999). A SS training session typically includes specific drills, choreographies, and physical conditioning exercises, imposing complex physiological demands, and its duration (~2 to 4 h) and intensity differ according to the age and level of the swimmers. Average training volumes of 15.1±3.5 h·wk⁻¹ for pre-juniors (pre-JR), 29.9±8.2 h·wk⁻¹ for juniors (JR), and 40.7±10.1 h·wk⁻¹ for seniors (SR) have been reported (Rodríguez-Zamora et al. 2012).

Despite the high requirements at such young ages, information about fluid intake and hydration during the strenuous training sessions is scarce (Lundy 2011). Moreover, different methods have been used to assess the state of dehydration of the swimmers, which makes comparisons challenging. In this context, the bioelectrical impedance vector analysis (BIVA) emerges as a non-invasive and safe technique for assessing hydration and body composition changes (Lukaski & Piccoli 2012).

This study applied BIVA to the assessment of hydration changes evoked during a typical training session in synchronised swimmers of different age and competitive level.

Method
Fifty-nine swimmers were classified into JR, according to FINA international age category, and pre-JR, the age category just below according to the Spanish federation (RFEN) rules. Stretched body height (h) and BM were assessed following the norms and procedures of the International Society for the Advancement of Kinanthropometry (ISAK). Fat mass (FM) and muscle mass (MM) were estimated from BIA measurements using the manufacturer’s default regression equations and are reported here for comparative purposes only. The subjects characteristics were: a) pre-JR: age 13.9±0.9 years, BM 47.0±7.2 kg, height 161.8±8.2 cm, fat mass (FM) 15.1±4.8% BM, muscle mass (MM) 37.6±5.0% BM; and b) JR: age 16.7±0.9 years, BM 53.7±4.9 kg, height 165.8±5.2 cm, FM 18.6±2.6%, MM 38.8±3.7%.

A multi-frequency wrist-to-ankle bioelectrical impedance (BIA) meter device (Z-Metrix®, BioparHom, France) was used and 50 kHz whole-body BIA vectors were analysed by the by the resistance (R) – reactance (Xc) graphic method, and standard Z mean values plotted (Piccoli et al. 1994). All BIA protocols and measurements were performed by internationally standardised criteria (NIH 1996). BIVA assessment was conducted immediately before (PRE) and after (POST) a typical training session (pre-JR 2.5±0.1 h; JR 4.0±0.2 h) in all swimmers.

BIVA approach was developed by Piccoli et al. (1994) and uses the plot of the impedance parameters resistance (R) and reactance (Xc) normalised for height (h) as a bivariate vector (Z) in the probabilistic R/Xc graph. The normalisation for height allows for the length of the conductor and thus provides a qualitative measure of soft tissue that does not depend on body size. The correlation between R and Xc determines the ellipsoidal form of the bivariate probability distributions (confidence intervals for average vectors and tolerance for individual vectors). The position and length of the vector provides
information about hydration status, body cell mass and cell integrity. A migration sideways of the vector due to low or high Xc indicates decrease or increase of dielectric mass (membranes and tissue interfaces) of soft tissues. The length of the vector indicates hydration status from fluid overload (decreased resistance, short vector) to exsiccosis (increased resistance, longer vector). Derived from these bioelectric direct measures (R/Xc), the phase angle (PA) of the impedance vector (Z) is calculated as arctangent: (Xc/R)·180°/π, in order to express both the amount and quality of soft tissue (Norman et al. 2012). PA has been suggested to be an indicator of cellular health (Mattar 1996; Zdolsek et al. 2000) where higher values reflect higher cellularity, cell membrane integrity and better cell function. In healthy subjects PA usually ranges between 5.0 and 7.0° (Bosy-Westphal et al. 2006) but values above 9.5° can be reached in some athletes (Torres et al. 2008).

Differences before PRE and POST were assessed by two-tailed paired t-test, with significance set at P<0.05. Correlation between height-normalised resistance and reactance (R/h and Xc/h) were assessed by Pearson’s correlation coefficient (r). Hotelling’s T² test determined differences in the complex localised vector through the 95% confidence and tolerance intervals.

**Results**

Descriptive values for body mass and bioelectrical variables before (PRE) and after (POST) the training session for each group, as well as mean differences and their significance, are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Changes in body mass and bioelectrical after a typical training session in pre-junior and junior swimmers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-junior (n=41)</strong></td>
</tr>
<tr>
<td>BM, kg</td>
</tr>
<tr>
<td>R/h, Ω/m</td>
</tr>
<tr>
<td>Xc/h, Ω/m</td>
</tr>
<tr>
<td>PA, Ω</td>
</tr>
<tr>
<td>Z, Ω</td>
</tr>
<tr>
<td>r (R/h, Xc/h)</td>
</tr>
<tr>
<td><strong>Junior (n=18)</strong></td>
</tr>
<tr>
<td>BM, kg</td>
</tr>
<tr>
<td>R/h, Ω/m</td>
</tr>
<tr>
<td>Xc/h, Ω/m</td>
</tr>
<tr>
<td>PA, Ω</td>
</tr>
<tr>
<td>Z, Ω</td>
</tr>
<tr>
<td>r (R/h, Xc/h)</td>
</tr>
</tbody>
</table>

BM, body mass; R, resistance; Xc, reactance; h, body height; PA, phase angle; Z, impedance module; r, Pearson linear correlation coefficient (R/h related to Xc/h). %Δ, percent differences PRE to POST; 95% CI, 95% confidence interval of the differences. *P<0.05 (paired t-test PRE vs. POST).

Loss in BM was greater in the pre-JR (-0.6 to -1.0% BM) than in JR swimmers (-0.3 to -0.7% BM). In contrast, BIVA showed vector migration in JR (T²=8.99; p<0.05), indicating moderate dehydration, whereas no significant changes were noted in pre-JR (T²=1.92; p>0.05) (Figure 1). All bioimpedance parameters were modified after the training session in both groups of swimmers, except the phase angle (PA).
**Discussion**

Our main finding was that bioimpedance vector analysis (BIVA) appears to be sensitive enough to detect small changes in the hydration status of young synchronised swimmers evoked by typical training sessions of long duration. Despite greater weight loss in the younger pre-JR swimmers (-0.6 to -1.0%) compared to JR swimmers (-0.3 to -0.7), BIVA showed significant vector migration in JR swimmers indicating a moderate degree of dehydration, whereas changes in the younger pre-JR swimmers were not significant despite showing a similar trend.

On the one hand, JR swimmers trained for longer time (~4 h) than the pre-JR (~2.5 h) in a relatively warm and humid environment, which would elicit greater losses in body fluids. This is consistent with the greater migration of the vector (i.e. increase in length), indicating a larger degree of dehydration. On the other hand, pre-JR swimmers showed greater weight loss compared to JR, which contrasts with BIVA results, thus showing discrepant results.

Only two field studies have examined the level of dehydration generated by SS training sessions, both with opposite results. Brown & Lundy (unpublished, cited in Lundy 2011) reported that 50% of components of the senior British team arrived at training dehydrated, defined as urine specific gravity ≥1.020, with a mean urine specific gravity of 1.021±0.004. Sweat losses monitored during the two sessions (240 min of dry-land training and 180 min of pool training) were small (258.0±49.0 mL/h during the dry session and 204.0±60.0 mL/h during the pool session). Fluid replacement was 78% during the dry-land session and 59% during the pool session, meaning that the swimmers were on average 0.4±0.5% dehydrated. These findings contrast with those of Pazikas et al. (2005), who showed a 2% loss in BM during an Olympic training camp session, most likely as a result of differences in environmental conditions and training intensity. Lundy (2011) notes that it is interesting to observe the lower fluid replacement during pool sessions, possibly because of limited drink breaks or to avoid gastrointestinal upset if practicing moves requiring the athlete to be upside down.

Our findings challenge the validity of the widespread use of changes in body weight as a practical tool to monitor the level of dehydration caused by intense training. It is now recognised that the assessment of body water is a dynamic and complex process, and that no measurement is valid for all situations (Armstrong 2005; McGarvey et al. 2010). As a matter of fact, regardless of age and
competitive level, a typical SS training session appears to affect the homeostatic hydration level of the swimmers, likely in proportion to the length of session and the environmental conditions. In this context, the BIVA emerges as a relative novel technique, precise, accurate, reliable, non-invasive, portable, inexpensive, safe, and simple to assess the hydration status in real time (Lukaski & Piccoli 2012). These properties are especially interesting for the assessment in sports, both of training process and competitive events. BIVA, different from other BIA methods, uses raw impedance parameters to provide information on hydration status, body cell mass and cell integrity without algorithm-inherent errors or requiring assumptions such as constant tissue hydration (Norman et al. 2012).

Conclusions
Bioimpedance vector analysis (BIVA) appears to be sensitive enough to detect small changes in the hydration status of young synchronised swimmers evoked by typical training sessions of long duration. Despite greater weight loss in the younger pre-JR swimmers (-0.6 to -1.0%) as compared to JR swimmers (-0.3 to -0.7), BIVA showed significant vector migration in JR swimmers only indicating a moderate degree of dehydration, whereas changes in the younger pre-JR swimmers were not significant despite showing a similar trend. These preliminary results should be considered by coaches, nutritionists, and physicians in order to ensure adequate fluid intake during training to avoid undesirable effects of hydration homeostasis disturbances.

References
**In-water resisted sprint swim training for age-group swimmers**

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**Keywords:** swim power, swim performance, growth and development, adolescents

**Introduction**

Worldwide, coaches employ training paradigms in an effort to maximise the performances of their athletes. In competitive swimming, a variety of methods have evolved as a means to improve swim performance, all of which focus on increasing swimmers’ abilities to develop propulsive force, decrease drag forces, or some combination of these factors. One accepted method used to improve propulsive force is an increase muscle size and function. There is some support that land-based resistive exercise increases muscle size, improves muscle function, and enhances motor skills with children and adolescents (Behringer et al. 2010; Harries et al. 2012). However, whether or not land-based resistive training enhances sport performance remains inconclusive in young athletes, due primarily to methodological and logistical discrepancies among previous studies. Further, land exercise does not commonly replicate actual swim movements, thus the extent to which it is useful in improving swim performance may be limited. Specific training methods would, at least theoretically, increase the likelihood of improving performance outcomes.

Swim power or ‘in-water’ resisted sprint swim training (IWRST) has been acknowledged by scientists and coaches to enhance sprint swim performance due to the specificity of training. Typical IWRST requires a cable connected to a spring balance scale (Julian & Coltune 1958), a rack-pulley system (Hopper 1975), or an elastic cord (Girold et al. 2007) whereby a swimmer is attached via a waist belt to the resistive load while swimming. IWRST has been previously suggested to invoke positive effects on adult swimmers (Aspenes & Karlsen 2012; Tanaka & Swensen 1998). Only one study has reported the use of IWRST in late adolescents (Girold et al. 2007). Studies using similar training paradigms with pre- or peri-adolescent (age-group) swimmers do not appear to exist.

The limited prevalence of research regarding IWRST in age-group swimmers may be attributable to the limited availability of training devices and/or other specialised equipment. More importantly, the lack of information regarding practical use and the efficacy of such training with age-group swimmers is likely an added deterrent. Whether or not IWRST, specific to age-group swimmers who are already actively training, is effective and advisable is currently dependent upon speculation. Therefore, data describing the benefits, or lack thereof, of IWRST in the adolescent population are needed. The purpose of this study was to examine the efficacy of IWRST on sprint swim performance and muscle mass in age-group swimmers when compared with traditional non-resisted sprint swim training.

**Methods**

**Participants:** Participants were recruited from a local, competitive, USA Swimming affiliated swim club. Before the beginning of any engagement with the participants, the University Institutional Review Board reviewed the protocol and methods, and ethics consent was granted through the University ethics committee. The participants and their guardians were informed of any potential risks involved in study participation, and all provided written informed consent in accordance to institutional regulation. Eighteen well-trained age-group swimmers (age 10.6 to 14.8 years) participated in the study. They were randomly assigned to one of two sprint swim training groups: resisted sprint swim training (RST; n = 10, five girls and five boys) and non-resisted sprint swim training (ST; n = 8, four girls and four boys). The characteristics of the swimmers in each group are displayed in Table 1. All swimmers trained in the same practice group under identical coaching and...
completed the same workouts for five months before the study (6 day-wk\(^{-1}\), 1.5 hr-session\(^{-1}\), average 3000 m-session\(^{-1}\)) and throughout the 10 weeks of the study period (6 day-wk\(^{-1}\), 1.5 to 2 hr session\(^{-1}\), average 3800 m-session\(^{-1}\)). All swimmers had participated previously in traditional swim training but had no prior experience with IWRST.

Swim power measurements: The intervention period occurred during the mid-season training (mid-May to mid-July, 2013). During the three weeks prior to the intervention, all participants were familiarised with the testing procedures. Progressive swim power tests using a modified commercial semi-tethered (resisted) swim training device, Power-rack (Black Stack; Jerden Industries, Inc., USA), were used to determine an individual’s excess peak power (PP) and excess peak power per stroke (PP-STK\(^{-1}\)) at weeks 0 (pre), 5 (mid), and 11 (post). The Power-rack is a system of pulleys and weights that allows a swimmer to be semi-tethered via waist belt to a resistive load while swimming. PP was defined as the highest swim power expressed as a product of the resistive workload and average speed for a 10-meter sprint. PP-STK\(^{-1}\) was defined as the highest value of PP per stroke. The term excess is employed above as the power required to generate the propulsive power necessary to swim at any given test speed could not be quantified. Only the power in excess of this theoretical power is measured and this is done by simply adding a resistive load and measuring the resultant speed. As many as ten 10-meter bouts at maximum effort were required for determining PP and PP-STK\(^{-1}\), and ad libitum rest (1 to 1.5 minutes) between repetitions was provided. Each repetition performed was assumed to be maximal effort. During each bout, total time and the number of strokes that the swimmer took were recorded. Approximately four newtons of resistive load were added with each successive bout until PP and PP-STK\(^{-1}\) were obtained, with the starting workload determined during the familiarisation sessions. The criteria to end a test were: 1) on a basis of time at the initial workload, when the swimmer adds more than four seconds to travel 10 meters; 2) on a basis of stroke number at the initial workload, when the swimmer adds more than five strokes; and/or 3) two to three trials after an obvious decline in power output was observed.

Swim performance tests: Maximum average swim speed was recorded as the mean ‘flag-to-flag’ (13.7 meters) speed during two 22.85-meter freestyle sprints (V\(_{\text{MAX}}\)13.7). These were performed prior to the progressive swim power test. The mean speed determined from two 50-meter long course freestyle competition times (V\(_{\text{MAX}50}\)) was also acquired. Speed and velocity are used interchangeably here as a swimmer’s direction is assumed to be essentially two-dimensional (along a horizontal straight line from one end of the pool to the other).

Muscle size and mass measurements: B-mode ultrasonographic muscle and adipose tissue thicknesses (MTT and ATT, respectively) were measured at weeks 0 and 11 using a real-time linear electronic scanner with a 5 MHz scanning head (Aloka SSD-500, Tokyo, Japan) at nine sites on the anterior and posterior aspects of the body (forearm, upper arm, trunk, thigh, and lower leg). From this measurement, estimates of total and regional skeletal muscle mass (SMM) and percentage fat (%Fat) were obtained (Midorikawa et al. 2009; Midorikawa et al. 2011).

Training protocols: IWRST using the Power-rack was completed twice per week for 10 weeks (Mondays and Wednesdays), consisting of 10 repetitions of 10-meter sprint swimming on a 1-minute interval against a resistive load set at 70-80% of the PP-STK\(^{-1}\) workload. The training load was later modified to remain within this 70-80% range after the mid-test when a noticeable increase in PP-STK\(^{-1}\) was observed. The resistive load varied among swimmers such that a swimmer could complete a 10-meter resistive sprint in approximately 10 seconds or less. ST performed the same sprint set without the resistive load at the same time as RST. On the days of testing or training interventions, all swimmers underwent the same warm-up procedure as directed by the coach. Following the resisted or non-resisted sprint swim training, all swimmers practiced stroke mechanics for the remainder of the session.

Statistical analysis: Data are shown as mean ± standard deviation (SD). A 2 x 2 mixed-design ANOVA (group × time) was used to assess the effect of training interventions (RST and ST) on dependent
variables for the 10-week time period. Partial eta-squared ($\eta^2_p$) was used to report estimates of effect size for the main effects and interactions. Pearson product-moment correlation coefficients were generated to assess relationships among performance variables at weeks 0 and 11 and to establish whether or not an improvement in $V_{\text{MAX}}$50 was associated with changes in muscle and swim power measures and $V_{\text{MAX}}$13.7. For all statistical analysis, IBM SPSS Statistics 20 for Windows (Armonk, NY: IBM Corp.) was used with the alpha level set at 0.05.

**Results**

During the three-week familiarisation period, the swimmers increased PP and PP·STK by 6.5% ($p = 0.09, \eta^2_p = 0.23$) and 6.4% ($p = 0.27, \eta^2_p = 0.11$), respectively. At the baseline measurement (week 0), there was no difference in age, competitive experience, anthropometric values, body composition, or swim power and performances between training groups (Tables 1 and 2).

Anthropometric, body composition, and performance data at week 0 and 11 are shown in Tables 1 and 2. Two-way mixed-design ANOVA revealed no group $\times$ time interaction for any measured variables. However, there was a significant main effect for time in many dependent measures, irrespective of training groups. Following seven weeks of training, an increase in height ($F_{(1,14)} = 21.67, p < 0.001, \eta^2_p = 0.61$) and decreases in the sum of ATT at nine sites ($F_{(1,14)} = 5.23, p = 0.038, \eta^2_p = 0.27$) and %Fat ($F_{(1,14)} = 7.95, p = 0.014, \eta^2_p = 0.36$) were observed. The sum was not a significant change in weight in both groups. Proximal limb length increased: upper arm ($F_{(1,14)} = 10.80, p < 0.01, \eta^2_p = 0.44$) and thigh ($F_{(1,14)} = 4.93, p < 0.05, \eta^2_p = 0.26$). There were increases in MTT at abdomen (8.9 and 6.0% for RST and ST, respectively; $F_{(1,14)} = 12.75, p < 0.01, \eta^2_p = 0.43$) and anterior (2.6 and 2.7%; $F_{(1,14)} = 8.94, p < 0.01, \eta^2_p = 0.35$) and posterior (6.7 and 0.7%; $F_{(1,14)} = 11.33, p < 0.01, \eta^2_p = 0.38$) mid-thigh. The sum of MTT at nine sites ($F_{(1,14)} = 20.60, p < 0.001, \eta^2_p = 0.60$) and SMM ($F_{(1,14)} = 27.92, p < 0.001, \eta^2_p = 0.67$) increased. Improvements in swim power and performance measures were also demonstrated after the 10 weeks (Table 2): PP, $F_{(1,14)} = 46.56, p < 0.001, \eta^2_p = 0.77$; PP·STK, $F_{(1,14)} = 29.67, p < 0.001, \eta^2_p = 0.68$; $V_{\text{MAX}}$13.7, $F_{(1,14)} = 29.03, p < 0.001, \eta^2_p = 0.68$; and $V_{\text{MAX}}$50, $F_{(1,14)} = 22.75, p < 0.001, \eta^2_p = 0.62$.

**Table 1**

| Anthropometric characteristics and body composition of the participants at weeks 0 and 11 |
|-----------------------------------------------|-----------------------------------------------|
| Resisted Sprint Training                      | Sprint Training                                |
| Week 0            | Week 11                  | %Δ       | Week 0            | Week 11                  | %Δ       |
| Age (year)        | 13.5 ± 1.0               | 13.5 ± 1.4 |                     |                            |           |
| Experience (year) | 4.6 ± 1.7                | 4.0 ± 1.7  |                     |                            |           |
| Height (cm)       | 163.3 ± 8.1              | 164.4 ± 8.5 | 0.7 *              | 166.1 ± 9.3               | 167.2 ± 9.0 | 0.7 * | 0.92 | 0.00 |
| Weight (kg)       | 57.9 ± 12.1              | 57.8 ± 11.6 | -0.1               | 55.6 ± 12.2               | 56.6 ± 11.5 | 1.7   | 0.20 | 0.12 |
| Arm span (cm)     | 165.8 ± 9.4              | 167.4 ± 8.6 | 1.0 *              | 167.8 ± 9.8               | 170.0 ± 9.3 | 1.3   | 0.32 | 0.07 |
| Forearm (cm)      | 24.0 ± 1.4               | 24.0 ± 1.3  | 0.2                 | 23.9 ± 1.4                | 24.0 ± 1.3  | 0.5   | 0.45 | 0.04 |
| Upper arm (cm)    | 31.1 ± 1.6               | 31.3 ± 1.7  | 0.8 *              | 31.4 ± 2.2                | 31.8 ± 2.1  | 1.2   | 0.52 | 0.03 |
| Thigh (cm)        | 38.9 ± 2.1               | 39.4 ± 2.2  | 1.3 *              | 39.8 ± 2.3                | 40.1 ± 2.0  | 0.6   | 0.47 | 0.04 |
| Lower leg (cm)    | 38.5 ± 4.0               | 39.5 ± 2.3  | 2.6                 | 40.1 ± 2.3                | 40.5 ± 2.2  | 0.9   | 0.56 | 0.03 |
| ATT$_{\text{sum}}$ (cm) | 92.7 ± 42.1             | 85.8 ± 39.1 | -7.5 *              | 72.3 ± 21.5               | 71.8 ± 26.4 | -0.7  | 0.07 | 0.22 |
| %Fat              | 21.3 ± 8.1               | 19.7 ± 8.1  | -7.2 *              | 17.3 ± 4.8                | 16.8 ± 6.0  | -2.6  | 0.15 | 0.15 |

%Δ, relative change between weeks 0 and 11; $\eta^2_p$, partial eta-squared; Experience, competitive swimming experience; ATT$_{\text{sum}}$, sum of adipose tissue thickness at nine sites of the body; %Fat, percentage fat.

* Difference between weeks 0 and 11 ($p < 0.05$).
Table 2 Muscle size, swim power, and swim performance data before and after the 10-week of training

<table>
<thead>
<tr>
<th></th>
<th>Resisted Sprint Training</th>
<th>Sprint Training</th>
<th>group × time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Week 0</td>
<td>Week 11</td>
<td>%Δ</td>
</tr>
<tr>
<td>MTTsum (cm)</td>
<td>296.2 ± 33.8</td>
<td>307.2 ± 34.3</td>
<td>3.0 *</td>
</tr>
<tr>
<td>SMM (kg)</td>
<td>18.6 ± 5.3</td>
<td>19.7 ± 5.5</td>
<td>5.9 *</td>
</tr>
<tr>
<td>Resistive training load (N)</td>
<td>25.3 ± 8.5</td>
<td>29.3 ± 9.6</td>
<td>16.5 *</td>
</tr>
<tr>
<td>Training velocity (m·sec⁻¹)</td>
<td>1.11 ± 0.13</td>
<td>1.10 ± 0.11</td>
<td>-0.4</td>
</tr>
<tr>
<td>PP (W)</td>
<td>35.4 ± 12.1</td>
<td>46.0 ± 16.7</td>
<td>29.9 *</td>
</tr>
<tr>
<td>PP·STK⁻¹ (W·STK⁻¹)</td>
<td>2.07 ± 0.87</td>
<td>2.50 ± 1.02</td>
<td>20.8 *</td>
</tr>
<tr>
<td>VMAX13.7 (m·sec⁻¹)</td>
<td>1.51 ± 0.13</td>
<td>1.54 ± 0.13</td>
<td>2.0</td>
</tr>
<tr>
<td>VMAX50 (m·sec⁻¹)</td>
<td>1.57 ± 0.15</td>
<td>1.63 ± 0.15</td>
<td>3.8 *</td>
</tr>
</tbody>
</table>

%Δ, relative change between weeks 0 and 11; η², partial eta-squared; MTTsum, sum of muscle tissue thickness at nine sites; SMM, skeletal muscle mass; PP, peak power; PP·STK⁻¹, peak power per stroke; VMAX13.7 and VMAX50, maximal swim speed in 13.7-meter sprint freestyle and 50-meter competition freestyle, respectively. * Difference between weeks 0 and 11 (p < 0.05).

VMAX50 was correlated (p < 0.03) to SMM (r = 0.52 and 0.51 at weeks 0 and 11, respectively), PP (r = 0.80 and 0.88), PP·STK⁻¹ (r = 0.77 and 0.88), and VMAX13.7 (r = 0.92 and 0.94), whereas no relationship between the relative changes in VMAX50 and SMM or swim power and performance measures was found.

**Discussion**

Due primarily to a general lack of specificity associated with land training, IWRST is becoming popular among the coaches of mature swimmers, although the performance implications of the use of IWRST in adolescents are unknown. Thus, the purpose of this study was to examine the efficacy of IWRST on sprint swim performance and muscle mass in age-group swimmers. The primary finding of the present study was that commensurate improvements in swim power and sprint swim performance were demonstrated for both RST and ST after 10 weeks of training period. Furthermore, despite the additional resistive load in RST, no training-specific increases in SMM or muscle size were observed. These results suggest no difference in the efficacy of resisted and non-resisted sprint swim training paradigms (RST and ST) for enhancing sprint swim performance or increasing SMM in age-group swimmers.

The focal points in the present study were the application and efficacy of in-water swimming-specific resistance training (IWRST) on age-group swim performance. None of our subjects demonstrated difficulty adapting to the swim power testing or training procedures, and comparable improvements in swim power measures between groups logically suggest no learning effect of IWRST during the intervention period. We were careful to equate the overall sprint swim training protocols of the groups such that the differential factor between groups was only the resistive load but not total training ‘volume.’ PP was determined specific to the training mode used, and an individual resistive load relative to PP was utilised for each swimmer. Also, all participants were active throughout the study period but none of them enrolled in any other competitive sport training, and thus the results of either group should not have been biased. Assuming the control of possible extraneous variables that might affect performance was sufficient, then explanations of why IWRST had no additional effect on swim power and performance in age-group swimmers may be due to the trainability of the peri-adolescent athlete or limited nature of the additional resisted sprint stimulus.

Identifying reasons why age-group swimmers improved both sprint performance and swim power regardless of training modes is not trivial, but the effect of IWRST may be limited simply by the modest trainability of peri-adolescent swimmers. The trainability or physiological response to resistance training in adolescents is due, in large part, to developmental maturity (Behringer et al. 2010). In the case of the present study, the maturational status of the age-group swimmers may have overwhelmed any effect that the types of training had on the performance outcomes. Adolescence (puberty) is the stage of human development leading to accelerated growth and increased secretion of steroidal hormones (Borer 2003). Velocities of muscle growth are reported to increase during this time, and are closely associated with peak height velocity (Borer 2003). Perhaps the increased muscle
growth associated with the adolescent growth spurt accounted for the proportional improvements in the performance outcomes in both the RST and ST groups. Unfortunately, we were not approved to assess maturational status in the present study, and thus our data do not allow us to clarify maturational influences on the measured variables. Regardless, because the onset and timing of maturational events vary considerably among children (Borer 2003), effects and outcomes of resistive training are often complex and compromised.

One complex factor that is relevant in this discussion is the sex of the adolescent participants. The onset of the growth spurt and the timing of maturational events differ between sexes (Borer 2003). In the present study, although boy swimmers were significantly taller and more muscular than girl swimmers and despite being similar in age, there were no sex-related differences in swim power or performance recorded at baseline. In addition, no sex × time interaction or sex × time × group interaction was revealed for any measured variables, suggesting that comparable improvements in measured variables existed between sexes. However, the relationship between the relative improvement in $V_{\text{MAX}50}$ and age was significant for boys ($r = 0.67, p = 0.048$) but not girls ($r = 0.11, p = 0.773$). Because the average age at peak height velocity is 12 years for girls and 14 years for boys, the girl swimmers in the present study may have been in the middle of the crucial growth and maturational period when chronological age per se may not be the most important factor for adolescents’ performance. This would not have been true for the boys. The relationship between chronological and maturational age appears to dictate to some extent, the timing of performance improvements. Although this may have been the case for the girl swimmers, because we did not measure maturational status of the swimmers, this discussion is limited to mere speculation.

Significant relationships between the relative increases in $V_{\text{MAX}50}$ and muscle size, swim power measures, or $V_{\text{MAX}13.7}$ were not evident in this study despite the significant cross-sectional correlations among the variables at weeks 0 and 11. This suggests that improving sprint swim performance did not necessarily require a proportional increase in muscle size, swim power, or maximal swim speed. These variables are related to swim performance, but may not account for much of the variability in swim performance, especially for growing and maturing athletes. These results support the findings of Cronin & Sleivert (2005) suggesting that specific training for muscle size and power characteristics known to be related to isolated muscle performance, does not necessarily transfer or enhance sport performance. The transferability of strength and power gains from a given resistance training protocol to athletic performance is often small, mostly due to a lack of specificity to the athletic movement (Harries et al. 2012). The specific nature of the IWRST in this study should, in theory, improve swim performance, assuming that the training stimulus was adequate. However, it is possible that the training duration and/or resistive training load used for RST in the present study may have been insufficient relative to the other swim training performed by the swimmers. A 10-week of training duration has been described as ‘relatively short’ duration in the literature (Cronin & Sleivert 2005). However, given that a summer or ‘long course’ season for age-group swimmers may last 16 to 18 weeks in the U.S., ten weeks (plus three weeks pre-training) represent a typical duration of an intensive training program for age-group swimmers. Therefore, our results seem to provide meaningful and practical information that may possibly assist coaches in the development of future training paradigms. Observationally, the resistive load protocol used in this study is employed by many regional swim teams in the U.S., although admittedly, the source of this paradigm is unclear. Further investigation and development focused upon optimal resistive loads during IWRST for different levels of swimmers are recommended.

Swim power was measured as a function of mean swim speed for a 10-meter sprint and the resistive force. In the present study, PP and PP-STK occurred at 60.8 and 68.0% of $V_{\text{MAX}13.7}$, respectively. The resistive training load we imposed for RST (70-80% of the workload at PP-STK) permitted the mean swim speed for 10-meter sprints to be 73 ± 3% and 72 ± 3% of $V_{\text{MAX}13.7}$ during weeks 1-5 and 6-10, respectively. We targeted the 10-meter sprint swims to be completed within ten seconds so that the training should require maximal effort and be focused upon increases in power rather than any increases in cardio-pulmonary endurance. We also avoided resisting the swimmer to the extent that
significant changes in stroke mechanics (distance per stroke or stroke frequency) were evident as compared with $V_{\text{MAX}}$13.7 tests. Nevertheless, swimmers in RST showed improved swim power variables measured by the progressive swim power tests (Table 2). A constant progress in the mean swim power output during IWRST throughout the 10-week period were also observed (15.9 ± 8.3%, $p < 0.01$), which presumably was ascribed to increased training load (16.5%; Table 2, Figure 1 AB).

The observed disproportionate improvements in PP and $V_{\text{MAX}}$13.7 in this study (Table 2) are in agreement with the results of Toussaint et al. (1990). Using the MAD system for young swimmers aged 12.9 years at the beginning, the authors found improvements in PP (49.3%) and maximum velocity (11.7%) after 2.5 years of regular competitive swim training. This disproportionate improvement may partially be interpreted by the exponential relationship between the two factors. However, these results might indicate that the age-group swimmers become less efficient in their use of propulsive power (Figure 1C). Although we were unable to clarify these disproportionate improvements, one factor is assumed to be that the contribution of arms and leg-kicking power to the total swim power may have changed or a result of increased SMM. As a future study, we intend to examine how maximum arm and leg-kicking power along with swim power and swim speed increase through a season and during adolescence as a means to evaluate swim training paradigms and maturational influence.

It is concluded that sprint swim performance can be improved through sport-specific training in peri-adolescent swimmers. However, IWRST does not appear to be any more effective than traditional non-resisted sprint swim training when embedded into a common length season training plan. Despite relationships among sprint swim performance, SMM, and swim power and evidence of growth-related changes, no additional training-specific increases in SMM were evident. Further consideration and development of IWRST protocols and paradigms specific to age-group swimmers are recommended.

References


**Does four weeks of simple reaction time training improve start performance in swimming?**

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**Keywords:** start, sprint, performance, time to response

**Abstract**

**Background:** Start performance, as defined by time to 15-m, has been used as an indicator of overall performance in sprint swimming. However, there is limited information regarding the key time to response to start (RT) that influence swimming start performance. The aim of this study was to investigate the effect of RT training on start performance in sprint swimming trials.

**Methods:** Eight male French national sprint swimmers (17.5±0.9years, 174.0±0.1cm, 65.6±10.4kg) performed, before and after 4 weeks of training, 3 repetitions of squat jump (SJ), counter movement jump (CMJ) and start on swimming start block on a Microgate Optojump optical measurement system. Short-term training session consisted to plyometric session associated to 3 days a week, a swimming start training based on simple reaction time with different stimuli: visual, auditory, combined (visual and auditory).

**Results:** Pearson correlation revealed time to perform 15-m was inversely related with height performance in SJ (r=-0.82, p=0.013) and CMJ (r=-0.85, p=0.007) after but not before training (SJ: r=-0.61, p=0.111; CMJ: r=-0.60, p=0.113). Time to perform 15-m was significantly related to RT measured on the block during auditory swimming start before (r=0.89, p=0.019) and after training session (r=0.83, p=0.022). No significant relationship was found between the change in RT and the difference in the time to perform 15-m with training (r=0.61, p=0.109). Finally, there was no significant change in 15-m swimming start (before training: 6.81±0.56s vs. after training: 6.74±0.50s) with a small Effect size (Cohen’s d: 0.13).

**Conclusion:** This study provides start training with stimuli associated to plyometric training induced neuromuscular adaptations rather than strength improvement, which was directly transferable in swimming start condition.
Introduction

Swimming events can be decomposed into four contributing factors of which start phase accounted for up to 26% of race time during sprint trials [20]. The start phase is generally defined from the starting trigger until the swimmer’s head passes a point of 15-m into the pool [20] what includes the time response to start (RT) of swimmers. During the two last United States team trials (Ohama 2012, Indianapolis 2013), we observed that the time differences separated the Men’s 50-m freestyle winner of the second (Jones C., 21.59-s vs. Ervin A., 21.60-s, Ohama 2012) [14] and the Women’s 50-m freestyle winner of the second (Coughlin N., 24.97-s vs. Manuel S., 25.01-s, Indianapolis 2013) [14] was equivalent to the difference in RT, that was equal only 0.01 sec between both male swimmers (RT Jones: 0.66 vs. RT Ervin: 0.67-s) and 0.04 sec between both female counterparts (RT Coughlin: 0.64 vs. RT Manuel S.: 0.68-s), respectively [14]. Previously, Ervin A. and Hall G. won together the men’s Olympic game 50-m freestyle event (Sydney, Australia, 2000) in 21.98-s but with different RT (Ervin A.: 0.68-s vs. Hall G.: 0.73-s). Due to a slower RT (0.82-s), Van den Hoogenband P. took the third place in 22.03-s while he swam faster [14]. Recently, during the last FINA World Swimming Championships (Istanbul, Turkey, 2012), Hetlard also won the Men’s 50-m Breaststroke with only 0.02-s beforehand on Dugonjic (26.30 vs. 26.32-s) due to a greater RT (0.63-s vs. 0.74-s) [14]. Together, these results showed the importance of RT in sprint event whatever the gender or the swim specialty. Time analysis of different swimming competitions raised the question about the RT optimisation on overall swimming performance. Bussières [6] previously reported a significant relation between RT and 25-m sprint performance in 30 collegiate swimmers. de la Fuente and Arellano [12] also reported a significant increase in RT when swimmers received terminal knowledge of results after the ending each start execution. Hence, RT must be considered a skill dependent upon experience and learning [18, 25]. It has been already reported that sprint time was reduced in response to visual compared to auditory stimulus [21, 22]. Therefore, the aim of this study was to investigate the effect of RT training on start performance in male swimmers engaged in sprint events. Additionally, of lower limb strength improvement caused by plyometric training, we supposed that the chronic exposition of different stimuli (visual, auditory and both combined stimuli) increased the start performance due to an improvement of time response to start with RT training.

Method

Subjects. Eight trained sprint male swimmers (17.5 ± 0.9 years, 174.0 ± 0.1-cm, 65.6 ± 10.4-kg) of regional and national level participated in this study. They were free of cardiorespiratory disease and trained 10–12 times a week (57±2.2 km.week$^{-1}$). They all gave their free written consent according to the declaration of Helsinki and the local ethic committee approbation.

Testing. After a full explanation of experimental procedures and a standardised warm-up, subjects completed 5 min of submaximal vertical jumping for familiarisation then 3 repetitions per modality of Counter Movement (CMJ) and Squat (SJ) jumps with and without auditory and visual stimuli [13]. Finally, all swimmers performed 3 sprints of 15-m in front crawl using their preferential start technique (track-start) from a standard poolside mounted starting block under simulated race conditions. All starts are signaled by an automatic auditory stimulus. Each jump repetition and series was interspersed by a rest interval of 30 sec and 3-5 min, respectively. The flight time of jumps were measured with an accuracy of 1/1000 sec by the Optojump photoelectric cells system (Microgate, Bolzano, Italy). [3, 13]. Under simulated swimming competition, the optojump was mounted on the block to record time to response to start. Finally, time to perform the 15-m in front crawl was manually measured by an experimented official timekeeper.

Training session. During 4 weeks of aerobic development, all swimmers performed 20-min per session, 3 days a week, a start training based on simple reaction time with different stimuli: visual, auditory, tactile and combined (visual and auditory). This task was included in the warm-up of their usual training session. At the end of the warm-up, each swimmer performed 15-m front crawl as quick as possible with a simulated competition start. Additionally, plyometric training took place 2 days per week as described by a previous study [19].
Statsitics. Descriptive statistics are expressed as means and standard deviations (SD). The parametric t-Student test for paired data was used to compare the effect of time to reaction training on height jumps, time response to start order and 15-m sprint speed. The Significance alpha level was set at $p \leq 0.05$. Effect size (ES) was evaluated using Cohen’s d and characterised as small (0.2–0.4), medium (0.5–0.8), or large (>0.8) [7].

Results
Table 1 showed the height performance in SJ before and after training session. SJ performance without stimulus did not significantly increase with training ($p = 0.121$), with a small ES. Conversely, SJ performance increased significantly for auditory (medium ES) and visual (small ES) stimuli, but not for combined stimuli (small ES). The relative increases in jump height were not significantly greater for auditory ($8.5 \pm 10.2$) than for visual ($4.7 \pm 6.6$, $p = 0.157$) stimulus. Plyometric training also provided a 9.9% increase in CMJ ($28.2 \pm 4.9$ vs. $30.7 \pm 4.3$, $p = 0.014$) ranging from -3.6 to 25.5% with a medium ES (Cohen’s $d$: 0.54, effect size $r$: 0.26). Results from Pearson correlation revealed time to perform 15-m was inversely related with height performance in SJ ($r = -0.82$, $r^2 = 0.67$, $p = 0.013$) and CMJ ($r = -0.85$, $r^2 = 0.72$, $p = 0.007$) after but not before training ($r = -0.61$, $r^2 = 0.37$ (p = 0.111) and $r = -0.60$, $r^2 = 0.37$ (p = 0.113) for SJ and CMJ, respectively). Data regarding relevant changes in time response to jump or start were presented in table 2. No significant change was showed in RT to jump in all conditions (auditory, visual or combined stimuli) with a small (auditory and combined stimuli conditions) and medium (visual stimulus trial) EF. Training session induced a greater RT in swimming departure condition with a medium ES ($p = 0.014$, Cohen’s $d$: 0.47, effect size $r$: 0.23). Time to perform 15-m was significantly related to RT measured on the block during auditory swimming start before ($r = 0.89$, $r^2 = 0.80$, $p = 0.019$, n = 8) and after training session ($r = 0.83$, $r^2 = 0.69$, $p = 0.022$, n = 8). None significant relation was found between the change in RT and the difference in the time to perform 15-m with training ($r = 0.61$, $r^2 = 0.37$, $p = 0.109$, n = 8). Finally, there was no significant change in 15-m swimming start (before training: $6.81 \pm 0.56$ s vs. after training: $6.74 \pm 0.50$ s) with a small ES (Cohen’s $d$: 0.13, effect size $r$: 0.07).

Discussion
Starting times were significantly related to race times in most events regardless of the stroke [16]. Results from different studies suggested that higher peak force measured on the block leads to better overall start performance [20]. In the present study, greater CMJ height performance after training led to better start time. Previously, positive effect of plyometric training on swimming performance has been observed [2, 19]. Bishop et al. [2] reported 15% improvement in performance time when habitual aquatic training was associated to 2 h.week$^{-1}$ plyometric training. It has been established that a short-term plyometric training induced adaptive changes in neuromuscular function due to an increased neural drive to the agonist muscles and changes in the muscle activation strategies (i.e. improved intermuscular coordination) [15, 26]. Rather than strength improvement, our results suggested that short-term training sessions induced proprioceptive neuromuscular facilitation contraction pattern, which was transferable from CMJ to swimming start in our swimmers. Our results also indicated that start time was significantly related to RT. Cossor et Mason [10] earlier observed a strong correlation between RT and swimming start time among butterfly male semi-finalists and finalists at the 2000 Olympic Games ($r = 0.63$, $p < 0.05$, n = 10). Tønnessen et al. [25] also reported a significant relation between RT and overall running performance event in 1,319 international sprinters. An influence of performance level and experience on RT management has also been revealed [25]. Thomas and Thomas [24] attributed the greater RT in elite than non-elite athletes to the time spent on practice and professional competition.

Our data also indicated that start training, which consisted to dive after auditory, visual or both stimuli, significantly decreased RT.
Table 1  Effect of training on height performance in squat jump, expressed in cm

<table>
<thead>
<tr>
<th>Squat Jump (cm)</th>
<th>No stimulus</th>
<th>Visual stimulus V</th>
<th>Auditory Stimulus A</th>
<th>Combined V+ A stimuli</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before training</td>
<td>27.5 ± 4.0</td>
<td>21.5 ± 3.4</td>
<td>21.9 ± 4.3</td>
<td>22.7 ± 5.1</td>
</tr>
<tr>
<td>After training</td>
<td>28.8 ± 4.0</td>
<td>22.5 ± 3.4*</td>
<td>23.5 ± 3.0*</td>
<td>24.1 ± 3.8</td>
</tr>
<tr>
<td>Cohen’s d</td>
<td>0.32</td>
<td>0.29</td>
<td>0.43</td>
<td>0.31</td>
</tr>
<tr>
<td>Effect-size r</td>
<td>0.16</td>
<td>0.14</td>
<td>0.21</td>
<td>0.15</td>
</tr>
</tbody>
</table>

* Significant level of difference was set at p value < 0.05.

Table 2  Effect of training on time response to jump and to swimming start, expressed in sec

<table>
<thead>
<tr>
<th></th>
<th>Visual stimulus V</th>
<th>Auditory Stimulus A</th>
<th>Combined V+ A stimuli</th>
<th>Swimming block start</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before training</td>
<td>0.966 ± 0.049</td>
<td>0.876 ± 0.045</td>
<td>0.911 ± 0.058</td>
<td>1.169 ± 0.079</td>
</tr>
<tr>
<td>After training</td>
<td>0.945 ± 0.030</td>
<td>0.874 ± 0.045</td>
<td>0.922 ± 0.052</td>
<td>1.134 ± 0.068*</td>
</tr>
<tr>
<td>Cohen’s d</td>
<td>0.52</td>
<td>0.04</td>
<td>0.20</td>
<td>0.47</td>
</tr>
<tr>
<td>Effect-size r</td>
<td>0.25</td>
<td>0.02</td>
<td>0.09</td>
<td>0.23</td>
</tr>
</tbody>
</table>

* Significant level of difference was set at p value < 0.05.

Recently, Takeuchi et al. [23] demonstrated that processing speed training based on auditory and visual stimuli presentation induced neural changes in young adults. Visual stimulus could affect the pre-motor time (PMT), the earlier phase of RT [10]. Neural changes could induce an increase in agonist muscle preactivity in association to the inhibition of antagonist muscle co-activation. Together, these neuromuscular adaptations improved RT [1, 17]. Finally, familiarisation with training to swimming block start following a single order could explain the relation between SJ and CMJ height performance to time to perform 15-m after training. Engaged in national competitions, our swimmers usually focused their attention on auditory signals. The greater precision of audition for temporal judgments [5] as well the level of practice could explain the auditory dominance during combined auditory and visual stimuli presentation, which was not changed by our short-term training sessions. Finally, the single auditory order to start of Optojump could explicate the longer RT to start of our subjects compared to the literature. Previously, Bredner and Welford [4] reported a faster RT when subject has been warned that a stimulus will arrive. In conjunction with ‘go’ signal, prior acoustic stimulus eliciting a startle response greatly reducing RT [9].

In conclusion, our data showed that time response to start was related to swimming start. We can assume that start training with auditory and visual stimuli associated to plyometric training induced neuromuscular adaptations rather than strength improvement, which was directly transferable in swimming start condition. Learning to start to a signal should be integrated into the swimming training.

References


**The interplay of critical velocity and anaerobic distance capacity and their relationship to competition performance**

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**Keywords:** critical velocity, anaerobic distance capacity, swimming performance, physiology

**Abstract**

Introduction: While critical velocity (CV) and anaerobic distance capacity (ADC) have been measured in swimming for many years, the relationship between these two measures of performance capacity, as well as their relationship to competition performance, has not been thoroughly detailed.

Methods: National level junior swimmers (22 males, 26 females, age = 15.8 ± 1.2 y; mean ± SD) completed a 400 m, 200 m and 100 m freestyle maximal effort time trial on consecutive days. A subgroup of 22 athletes (8 males, 14 females) also completed four 25 m maximal freestyle efforts, from which the fastest effort was recorded. Critical velocity was measured as the slope of the regression line for the three maximal effort time trials, and the ADC was established as the intercept of this line and the y-axis. Competition performance within 3 months prior to CV testing was compiled and expressed relative to the world record (WR). The swimmers’ best event was the race for which they were closest to WR.

Results: Critical velocity and ADC were negatively correlated (p < 0.001) for both male (r = -0.75, -0.88 to -0.54; r-value, 90% confidence interval) and female (r = -0.72, -0.52 to -0.85) swimmers. In the freestyle sub-group, the ADC and fastest 25m performance were also highly negatively correlated (p < 0.01) for both males (r = -0.96, -0.82 to -0.99) and females (r = -0.72, -0.38 to -0.89). Across both male and female athletes a 5 m higher ADC corresponded to a decrease in CV of 0.05 m.s\(^{-1}\). Female swimmers whose preference was a 400 m event had 6.1 to 8.5% faster CV values when compared to all other distances, the same was found for male 1500 m swimmers compared to male 100 m swimmers, 7.1% faster. Critical velocity was also significantly correlated with competition performance regardless of stroke or distance for males (r = -0.59, -0.79 to -0.29), and for performance in 200 m events regardless of stroke for females (Spearman’s rho = -0.49, -0.75 to -0.07, p < 0.05, n = 20). Female swimmers also had a significant negative correlation between ADC and 100 m performance regardless of stroke (r = -0.50, -0.73 to -0.16, p < 0.05, n = 21).

Conclusions: The moderate negative relationship between CV and ADC fits well with the conventional notion that swimmers often exhibit either an aerobic or anaerobic orientation. While both systems can be improved with training, different swimmers often focus on one system, potentially to the detriment of the development of the other. The CV-ADC relationship may provide insight into the potential effects of having an excessive focus on one energy system in training. It appears junior male freestyle swimmers exploit their anaerobic capacity to a greater degree than junior female swimmers over 25 m. Critical velocity and ADC are also related to 100 m competition performance, further strengthening the case for their use in the monitoring of swimmers.

**Introduction**

Monitoring of swimmers’ responses to training is an essential part of any successful elite swimming program. However, it is not always practical to conduct testing on large numbers of athletes using standard physiological testing protocols such as the 7 x 200 m step test (Pyne et al. 2001) that require extensive staffing and resources. A solution has been the development of simple, performance-based testing such as the critical velocity (CV) test, which provides information about two important components which relate to swimming performance. The first, critical velocity, is an estimate of the velocity at the onset of blood lactate accumulation (Wakayoshi et al. 1993, Takahashi et al. 2009). The
second component is anaerobic distance capacity (ADC) which is a surrogate estimate of the amount of energy a swimmer can produce above the metabolic power output required to maintain CV in a single effort (Skiba et al. 2012).

The components of the CV model are calculated using a series of maximal effort swims over varying distances. Distances are plotted on the y axis and the times that correspond to these on the x axis and a regression line calculated (Wakayoshi et al. 1993). The slope of the regression line is the CV, in m.s$^{-1}$, and the intercept of the y axis is the ADC. Anaerobic distance capacity is measured in metres but, as previously stated, should be thought of as a finite anaerobic work capacity (in kJ) over which this distance could be covered with the energy cost of swimming at maximal velocity. Critical velocity has been validated as an indicator of lactate threshold (Wakayoshi et al. 1993, Takahashi et al. 2009), a factor which has been related to the maintenance of maximal swimming velocity (Thompson et al. 2006; Anderson et al. 2008) and is responsive to swimming training (Toubekis et al. 2011; Pyne et al. 2001; Anderson et al. 2006). However the use of ADC in swimming has been less consistent, with some research suggesting that this measure is not related to the maintenance of maximal swimming velocity (Dekerle et al. 2002). Anaerobic Distance Capacity may relate more strongly to maximal accumulated oxygen deficit rather than the maintenance of maximal velocity. However to the authors’ knowledge this relationship has not been investigated in swimming.

It follows logically that CV must be related to performance as it is calculated from a series of maximal efforts. However, it is unknown whether the measurement of this component in freestyle is related to performances in other strokes. The purpose of this study was to determine whether CV and ADC measures calculated in freestyle correspond to swimming performance regardless of stroke. A secondary aim of this investigation was to characterise the relationship between the ADC and performance, both in the stroke it has been measured in and across different strokes.

**Methods**

Forty eight national level junior swimmers (22 males, 26 females, age 15.8 ± 1.2 y; mean ± SD) completed this series of tests as a part of a week-long national training camp at the Australian Institute of Sport in Canberra

All swimmers completed, in the following order, a 400 m, 200 m or 100 m freestyle maximal effort time trial on three consecutive days. These were completed with a standard competition start and were electronically timed (Omega, Switzerland). Each time trial followed a standardised warm up which concluded five minutes prior to the maximal effort. All maximal efforts were completed in the morning to limit the effect of circadian rhythm on performance. These time trials were then plotted, with distance on the y axis and time on the x axis, and a linear regression calculated for each individual swimmer. The two characteristics of this line, the slope and the intercept terms, were then used as measures of CV and ADC respectively, as is the standard practice for calculating these components (Wakayoshi et al. 1993).

A sub-group of 22 swimmers (8 males, 14 females, age 16.0 ± 1.1 y) also completed four 25 m maximal freestyle efforts on a 6 min time cycle to allow for full recovery, from which the fastest effort was recorded and utilised in this analysis. These efforts were completed the day following the 100 m freestyle time trial. One subject was excluded from this analysis from the female cohort as she was 3 standard deviations from the mean for 25 m time leaving a total of 13 female athletes in the analysis.

Publicly available results from all major competitions within the three months prior to testing were sourced from state swimming association websites and included in this analysis. The fastest result in each event the swimmer competed in at these competitions was included. These results were then converted to a percentage of the current world record (WR) for that particular gender, distance, stroke and pool length. The event that had the lowest value for this measure, ie the closest to world record, was then recorded as the athlete’s best stroke and distance. 100 m and 200 m performances in the same stroke as the individual’s best performance were also analysed. Swimmers’ best 100 m
and 200 m races were only included when the swimmers’ best result for that distance was in the same stroke as the swimmer’s best event. Where this was not the case, for example if a butterfly swimmer had not completed a 200 m butterfly race and therefore their best event over 200 m was in freestyle, the swimmer was excluded from this section of the analysis.

All variables were analysed for normal distribution using the Shapiro-Wilks test. Where variables were not normally distributed Spearman’s rank correlations were used, otherwise a Pearson’s product-moment correlation analysis was undertaken. Correlation descriptors of large ($r \geq 0.5$), moderate ($r = 0.3$ to 0.49) and small ($r < 0.3$) were used (Cohen 1988). Confidence limits (90%) were used for all correlations and significance was set at $p < 0.05$. An ANOVA with a Tukey post-hoc test was used to analyse differences in means in CV between best events—significance was set at $p < 0.05$.

**Results**

There were large negative correlations between CV and ADC for both males ($r = -0.75, -0.88$ to $-0.54$; $r$ value, 90% confidence limits, $p < 0.001$) and females ($r = -0.72, -0.85$ to $-0.52$, $p < 0.001$) as can be seen in Figure 1. These relationships indicated that between individuals an increase of 5 m in ADC corresponded to an average decrease in CV of 0.05 (0.03 to 0.06) m.s$^{-1}$ (mean 90% confidence limits) for both females and males. This speed increment is equivalent to a difference of 2.5 s per 100 m when CV decreases from 1.45 to 1.40 m.s$^{-1}$.

A large correlation was evident between CV and the percent of WR for a swimmer’s best event for males ($r = -0.59, -0.78$ to $-0.29$). An improvement in CV from 1.40 to 1.45 m.s$^{-1}$ corresponded to a mean improvement of 1.68 (0.79 to 2.57) % in relation to the WR for their best event. However this relationship was not significant for the female cohort of this investigation ($\rho = -0.21, -0.53$ to 0.14, $p = 0.29$).

Non-significant relationships were found between ADC and percent of WR in swimmers’ best events for male ($r = 0.27, -0.11$ to 0.57, $p = 0.23$) and female ($r = -0.16, -0.47$ to 0.18, $p = 0.43$) participants.

![Figure 1: Correlations between critical velocity and anaerobic distance capacity for males (filled data points, solid and dashed lines; data, mean regression, 90% CL) and females (open data points, dotted and dot-dashed lines)](image-url)
Table 2 shows a 7.1% higher mean CV value for male 1500 m swimmers compared to 100 m specialists and 6.1 to 8.5% higher mean CV values for female 400 m swimmers when compared to swimmers with preferences for shorter distances. Anaerobic distance capacity was seen to be 53.1% greater for male 100 m swimmers compared to male 1500 m swimmers, and 400 m female swimmers had ADC values 40.9% lower than 100 m swimmers and 53.3% less than 50 m swimmers.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Gender</th>
<th>50 m</th>
<th>100 m</th>
<th>200 m</th>
<th>400 m</th>
<th>1500 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Velocity (m.s⁻¹)</td>
<td>Male</td>
<td>1.42 (0.04)</td>
<td>1.41 (0.03) *</td>
<td>1.44 (0.04)</td>
<td>1.51 (N/A)</td>
<td>1.51 (0.07)</td>
</tr>
<tr>
<td>Critical Velocity (m.s⁻¹)</td>
<td>Female</td>
<td>1.29 (0.06) *</td>
<td>1.30 (0.05) *</td>
<td>1.32 (0.04) *</td>
<td>1.40 (0.02) *</td>
<td>-</td>
</tr>
<tr>
<td>Anaerobic Distance Capacity (m)</td>
<td>Male</td>
<td>23.46 (2.11)</td>
<td>24.85 (3.75) *</td>
<td>20.55 (3.15)</td>
<td>17.95 (N/A)</td>
<td>16.23 (5.06)</td>
</tr>
<tr>
<td>Anaerobic Distance Capacity (m)</td>
<td>Female</td>
<td>22.72 (2.02) *</td>
<td>20.88 (3.89) *</td>
<td>18.16 (3.70) *</td>
<td>14.82 (1.33)</td>
<td>-</td>
</tr>
</tbody>
</table>

Values: mean (SD). * For male: significantly different to 1500 m swimmers, for female: significantly different to 400 m swimmers.

When comparing ADC to percent of WR for 100 m of each swimmer’s specialist stroke, female swimmers had a significant negative correlation ($r = -0.44, -0.73 to -0.02, p = 0.09, n=21$), indicating that an improvement of 5 m for ADC corresponded an average improvement of 1.60 (0.79 to 2.57) % in time relative to WR. For males this relationship was not as pronounced and did not reach significance ($r = -0.44, -0.73 to -0.02, p = 0.09, n=21$) but the magnitude of mean change was similar, with a 5 m change in ADC corresponding to a mean change of 2.30 (0.11 to 4.49) % in time relative to WR.

When compared to 200 m performance relative to WR it was CV, not ADC that was more highly related. While ADC did not show any significant relationship for this distance, CV had a significant rank correlation (200 m data for females were non-parametric) to percent of 200 m WR for females ($r = -0.49, -0.75 to -0.07, p < 0.05, n=20$) and was approaching significance for a Pearson’s correlation for males ($r = -0.42, -0.69 to -0.05, p = 0.07, n = 20$).

For the subset of freestyle specialists there were significant negative correlations between fastest time to 25 m and ADC. For men ($r = -0.96, -0.99 to -0.82, p < 0.001, n = 8$) a 5 m change in ADC corresponded to a 0.39 (0.29 to 0.48) s improvement in 25 m time, for women ($r = -0.72, -0.91 to -0.29, p < 0.01, n = 13$) a 5 m change in ADC corresponded to a 0.32 (0.16 to 0.49) s improvement in performance time over 25 m.

**Discussion**

While the critical velocity (CV) and anaerobic distance capacity (ADC) have been researched previously the relationship between the two has not been thoroughly detailed. This study indicates that in a cohort of highly-trained age group swimmers the two measures have a large negative relationship. This outcome fits well with the conventional notion that swimmers often have a bias towards producing energy either aerobically or anaerobically. Swimmers may focus on one system in their training to the detriment of the other. The results from this study showed that for a 5 m improvement in ADC, which may be brought about through a change in (anaerobic) training focus, there can be an associated decrease of approximately 0.05 m.s⁻¹ in CV (aerobic fitness). While this antagonistic change may occur with a singular training focus, if coaches are aware of, and are better able to measure, these components they may be able to limit or even stop the decrease in aerobic fitness while increasing the capacity of the anaerobic energy pathway.

The results presented in relation to event preference suggest that assessment of CV and ADC could be useful in assessing the aerobic/anaerobic bias. Higher CVs were evident for 400 m female swimmers.
compared to all other distances, and for 1500 m male swimmers compared to 100 m male swimmers. However, all swimmers who had a preference for an event of 400 m or longer were freestyle specialists, which may have exaggerated this relationship. Regardless, moderate to large relationships were observed between CV and ADC and 100 m and 200 m performance despite stroke differences suggesting that the observed differences were related to both freestyle technique and energetic pathways.

Critical velocity was seen to be a significant contributor to performance across all best events for the male cohort in this study. This relationship was highly variable between swimmers, and increased in variation the closer to the WR swimmers were, potentially reflecting the increased specialisation seen at higher performance levels. Despite this variation CV decreased as athletes’ best performances moved further away from the WR, suggesting that CV is an important component related to performance. Non-significant results were observed for the female group. This may relate to decreased level of freestyle technical ability relative to their stroke speciality compared to the male swimmers, although this cannot be verified as no index of technical ability aside from swimming speed was measured.

Anaerobic distance capacity correlated significantly with performance over 100 m regardless of stroke for females, however CV did not. This difference is likely due to the relevance of these components to the 100 m event which typically lasts 55 to 75 s for females depending on stroke. This event utilises a large relative contribution from the anaerobic energy system in female athletes, 48.6% (Rodriguez & Mader 2003) and the duration over which this event occurs means that lactate threshold is much less of a limitation on performance when compared to anaerobic capacity (Weyand et al. 1994). Critical velocity was significantly correlated with 200 m performance for females regardless of stroke, while ADC was not. Again this may be due to the nature of the event which draws ≈ 70% of energy from the aerobic system and ≈ 30% from the anaerobic system (Zamparo et al. 2000) (data from a mixed gender sample) and has a duration of 115 to 160 s. This means that anaerobic metabolite accumulation has a larger contribution to limiting performance compared to the 100 m distance (Weyand et al. 1994). For the male subset the same trends were observed, however they did not reach significance. This may have been due to smaller subject numbers in some of the analyses or greater inter-subject variability within the male cohort.

This study also found a high correlation between 25 m time and ADC for the male and female freestyle subset of swimmers. This outcome strengthens the use of ADC as an indicator of ‘anaerobic ability’. This observation was made despite 25 m performance being too short to fully expend anaerobic capacity (Vanhatalo et al. 2007) and thus performance is more likely limited by shortcomings in anaerobic power. Anaerobic distance capacity is a theoretical indicator of the anaerobic capacity, capacity and power are intertwined as training specific to one will affect the other (Medbo & Burgers 1990). Thus ADC may be useful in giving an indication of overall ‘anaerobic ability’ of swimmers.

While the findings of this study are useful, there are some limitations to the design. Competition results were within the three months prior to testing and a number of variables can affect performance and energetics over this time period. This limitation may have resulted in weaker relationships between measured variables and competition performance than if performance been measured closer to the study. Another limitation is the cross-sectional design of the study. While it may be useful to quantify between-subject differences in variables in a cohort of swimmers, a within-subject design where these variables are measured before and after a period of training and related to performances at these time points would allow for stronger inferences on individual responses.

This investigation indicates the utility of both the CV and ADC measures, their antagonistic relationship to each other and relevance to competition performance regardless of stroke specificity. The use of these measures may assist coaches in analysing their swimmers’ responses to training and, through the analysis of the reactions of both CV and ADC, provide some guidance on how future
prescription of training may affect them. Through trial and error this will allow coaches to understand how much they need to focus their training prescription on each system to either maintain or increase its capacity to produce energy, as well as how this differs between their athletes.

References


The contribution of the arm stroke and leg kick to freestyle swimming velocity, controlling for stroke and kick rate: a pilot study

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1School of Human Movement Studies, The University of Queensland, 2Queensland Academy of Sport, 3Swimming Australia, Qld

Keywords: metabolic cost, velocity, whole stroke, arm stroke, leg kick

Introduction

During maximal freestyle swimming it is generally accepted within the literature that the arms contribute approximately 90% to the total swimming velocity in elite swimmers [1, 2]. This
contribution has also been shown to be valid irrespective of swimming ability [3]. While some authors have taken this finding to imply that the leg kick contributes to only 10% of the velocity [4, 5], others have found that, when swimming with the leg kick only, swimmers can achieve approximately 60-65% of the velocity attained during whole body swimming [3]. Thus, when the reported contribution of the arms (~90%) is summed with the contribution of the legs (~60%), the result far exceeds the velocity achieved during whole body swimming (100%).

Previous research has also investigated the contributions of the arm stroke and leg kick to whole body energy expenditure. In studies where the anaerobic and aerobic capacities of arm stroke, leg kick and whole body freestyle swimming have been measured, the summation of arm stroke and leg kick energy expenditure have exceeded the total energy expenditure observed in whole body swimming [6-8]. Authors have suggested that synergistic stabilising muscles (e.g. trunk muscles) could be active in both the arms only and legs only trials. As a result, these muscles require O₂ in both instances and this energy overlap when summing the VO₂ values from arms only and legs only trials is not accounted for in whole body swimming. While this may be true, the difference between whole body swimming VO₂ and the sum of the VO₂ of arms only and legs only swimming is too great to be solely attributed to the double-up of the VO₂ requirements of the synergistic stabilising muscle groups [6]. Possible reasons for the discrepancy in previous findings could relate to the lack of measurement and control over stroke and kick rate across trials, as these parameters can influence swimming velocity as well as metabolic cost [5, 9]. If a swimmer’s stroke rate in the arms only trial exceeds that attained in the whole stroke trial, the swimmer is likely to achieve a higher velocity with higher energy expenditure compared to what would be observed if the stroke rate of the arms only trial matched that of the whole stroke trial. Allowing participants to swim the whole stroke trial, and the arms only and legs only trials with varying stroke and kick rate means that the internal mechanical power and metabolic demands are bound to exceed 100% when summed together. The contribution of the arm stroke and leg kick to swimming velocity, and the associated energy expenditure, while controlling for stroke and kick rate, is yet to be examined. The purpose of this study was to: 1) determine the contribution of the legs and arms to velocity in submaximal, steady-state freestyle swimming while controlling stroke and kick rate, and 2) determine the metabolic cost associated with whole stroke, arm stroke only and kick only freestyle swimming. A comprehensive understanding of the contribution of the upper and lower limbs to swimming velocity and metabolic cost will inform training prescription, with the aim of decreasing the metabolic costs associated with these movements while increasing the velocity contributions of the arm stroke and leg kick.

Method

Participants. Five trained swimmers (two females and three males) volunteered to participate in this study. Participants’ descriptive characteristics data are shown in Table 1. All participants had competed at the Queensland Swimming Championships in the previous month and were free from injury and illness. Participants were informed of the requirements of the study before giving their written consent and each was medically screened (Sports Medicine Australia Pre-Exercise Screening Questionnaire) prior to testing. The study was approved by the Medical Research Ethics Committee of The University of Queensland.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Participant characteristics for age, training age, body mass, height and 200 m freestyle personal best (PB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n = 5</td>
<td>Age (y)       Training age (y) Mass (kg) Height (cm) 200 m PB (s)</td>
</tr>
<tr>
<td>17.1 ± 1.6</td>
<td>9.0 ± 1.9 72.9 ± 8.7</td>
</tr>
</tbody>
</table>

All data are presented as mean ± standard deviation.

Procedures. Participants’ body mass and stature were measured using a calibrated set of digital scales (A&D HW-200KGL, AND, Australia) and stadiometer (Harpenden, Holtain, Crymych, UK), respectively. Each swimmer then performed a 400 m, low-intensity warm up of their choice which included two laps of familiarisation breathing through a modified medium Hans-Rudolph mouthpiece valve.
(combination of y-valve series 2630 and t-valve series 2600) and breathing tube setup, as pictured in Figure 1. The warm up was followed by a swim test set involving one 400 m whole stroke trial at 70% and 85% of participants best 200 m swim time; two 200 m arm stroke only trials, while matching the stroke rate achieved in the whole stroke trials at 70% and 85%; and two 200 m kick only trials, matching the kick rate achieved in the whole stroke trials at 70% and 85%. All tests were completed in an indoor 25 m pool.

Swimming velocity in the whole stroke trials was guided by underwater pacing lights (Pacer2Swim, Portugal). During the whole stroke trial, stroke and kick rate were recorded over three stroke cycles and eight kick cycles, respectively, once per 25 m lap. Stroke rate was recorded during the whole stroke and arm stroke only trials by manually timing three complete stroke cycles using a Seiko S141 stopwatch (Seiko, Tokyo, Japan). An underwater camera (GoPro HERO1, San Mateo, California) followed the swimmers from the side of the pool, enabling the calculation of kick rate in the whole stroke and kick only trials. In the arm stroke only trial, participants were instructed to match the stroke rate that was used in the whole stroke trial. An audible metronome (Tempo Trainer Pro, FINIS Inc., USA) placed inside the swimmer’s cap was programmed to emit an audio signal when the swimmer’s hand should be entering the water to help control the stroke rate. The same method was used in the kick only trial based on the kick rate recorded in the whole stroke trial. Stroke and kick rate were recorded in the arm stroke only and kick only trials, respectively, and compared to those recorded in the initial whole stroke trial.

The legs were supported by a pull buoy and band in the arm stroke only trial, and arms were rested on a kickboard in front of the swimmer in the kick only trial. During each trial, participants were instructed to perform a push off from the wall to start swimming, use open turns at the end of every 25 m lap instead of tumble turns, and commence swimming as soon as possible. The whole stroke trials were completed first for all participants; however the order of the arm stroke only and kick only trials were randomised. The order of intensity at which the whole stroke trials were completed was also randomised. Each trial was separated from the next by five minutes of passive rest.

During all trials, oxygen uptake ($\dot{V}O_2$) was measured using the K4b² telemetric gas analysis system (Cosmed, Rome, Italy) using the modified Hans Rudolph set up in Figure 1. The Cosmed K4b² was calibrated according to the manufacturer’s instructions prior to the each trial. The steady-state $\dot{V}O_2$ in the final minute of each trial was used for comparison. Absolute and relative metabolic cost were calculated following the equations of di Prampero [10]. Total swim time and each 25 m lap time were verified by video footage. Heart rate (HR; Polar T31, Polar, USA), blood lactate concentration ([La−]; Lactate Pro 2, Tokyo, Japan) and rating of perceived exertion (RPE; Borg’s 6-20 scale, [11]) were
recorded after each trial. All trials were video recorded with cameras (Sony HDV 1080i Mini, Sony, Japan) for verification of velocity and stroke rate.

Data was analysed using SPSS (version 22.0, SPSS, Inc., Chicago, IL). Normality of the distribution was tested using the Shapiro-Wilk test. Analyses included descriptive statistics and paired samples t-tests to identify potential differences in the velocity and VO₂ consumption in the arm stroke only and leg kick only swims compared to the whole stroke swims. Paired samples t-tests were also used to identify differences in these contributions between the two different intensities. Data are presented as mean ± SD unless otherwise specified and significance was set at p<0.05.

**Results**

A summary of VO₂ and velocity data is presented in Table 2. Absolute VO₂ during the arm stroke and leg kick trials were significantly lower than that observed in the whole stroke trial for both intensities (p<0.01). Arm stroke VO₂ and leg kick VO₂ corresponded to 74.5% and 73.8% of the whole body VO₂ at 70%, respectively. Interestingly, the relative VO₂ contributions observed in the 70% trials were not different to those observed in the 85% trials, which corresponded to 70.2% and 72.9% for arm stroke and leg kick trials, respectively (p>0.05). Differences in VO₂ between the two intensities was only significant for the arm stroke trials (p=0.005), while whole body and leg kick swimming approached significance (p=0.069 and p=0.066, respectively).

<table>
<thead>
<tr>
<th></th>
<th>VO₂</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AL</td>
<td>AO</td>
</tr>
<tr>
<td>70% Abs</td>
<td>2.7 ± 0.6</td>
<td>2.02 ± 0.4</td>
</tr>
<tr>
<td>%</td>
<td>100.0</td>
<td>74.5</td>
</tr>
<tr>
<td>85% Abs</td>
<td>3.3 ± 0.9</td>
<td>2.28 ± 0.5</td>
</tr>
<tr>
<td>%</td>
<td>100.0</td>
<td>70.2</td>
</tr>
</tbody>
</table>

AO: arm stroke only, LO: kick only, AL: whole stroke; *Significantly different to whole body swimming at the 0.05 level; ^Significantly different to whole body swimming at the 0.01 level

Swimming velocity in the arm stroke trials achieved 89.4% (p=0.002) and 88.8% (p=0.012) of the velocity achieved in the whole stroke trials at 70% and 85%, respectively. These contributions were significantly different to the contributions observed in the leg kicking trials (p<0.01), in which velocity corresponded to 63.7% (p<0.001) and 64.8% (p<0.001) of the velocity achieved in the whole stroke trials at 70% and 85%, respectively. The relative contributions of the arm stroke to velocity in the 70% and 85% trials were not different, nor were the relative contributions of the leg kick to velocity at either intensity (p>0.05).

The metabolic cost associated with each trial is reported in absolute and relative units in Table 3. Swimming with the arm stroke only required the least amount of energy compared to the whole stroke at 85% (p<0.05) and leg kicking trials at 70% and 85% (p<0.001). Regardless of the intensity and stroke and kick rate, swimming with the leg kick only required more energy per metre than the whole stroke (p<0.05) and arm stroke swimming (p<0.001).
Table 3  Absolute (J · m⁻¹) and relative (corrected for body mass; J · kg⁻¹ · m⁻¹) metabolic cost of the six swimming trials

<table>
<thead>
<tr>
<th></th>
<th>AL</th>
<th>AO</th>
<th>LO</th>
</tr>
</thead>
<tbody>
<tr>
<td>70%</td>
<td>828.6 ± 136.0</td>
<td>789.8 ± 180.1</td>
<td>974.2 ± 156.2*</td>
</tr>
<tr>
<td>Relative</td>
<td>11.3 ± 0.9</td>
<td>10.8 ± 2.0</td>
<td>13.3 ± 1.0*</td>
</tr>
<tr>
<td>85%</td>
<td>896.0 ± 181.9</td>
<td>713.0 ± 103.1*</td>
<td>1021.3 ± 98.4*</td>
</tr>
<tr>
<td>Relative</td>
<td>12.3 ± 2.2</td>
<td>9.8 ± 0.6*</td>
<td>14.1 ± 0.7*</td>
</tr>
</tbody>
</table>

* Significant difference compared to whole body swimming (p<0.05); # Significant difference between arms only and legs only (p<0.001)

A summary of [La⁻], HR, RPE, and stroke and kick rate data is presented in Table 4. No significant differences were found between whole stroke, arm stroke only and kick only in post-swim [La⁻], regardless of intensity. HR was significantly lower in the arms only trial compared to the whole stroke for 70% (p=0.038). A significantly lower HR was also observed in the arm stroke and leg kick trials compared to the 85% whole stroke trial (p=0.003 and p=0.037, respectively). A lower RPE was observed in the arm stroke trials for 70% (p=0.020) and 85% (p=0.041) compared to the whole stroke trials. No other significant differences were observed between [La⁻], HR and RPE.

Table 4  Mean ± SD HR, [La⁻], RPE, stroke rate (SR) and kick rate (KR) for each trial

<table>
<thead>
<tr>
<th></th>
<th>AL</th>
<th>AO</th>
<th>LO</th>
<th>AL</th>
<th>AO</th>
<th>LO</th>
</tr>
</thead>
<tbody>
<tr>
<td>70%</td>
<td>2.7 ± 1.2</td>
<td>2.2 ± 0.6</td>
<td>1.9 ± 0.3</td>
<td>3.9 ± 1.7</td>
<td>2.7 ± 0.9</td>
<td>2.6 ± 1.1</td>
</tr>
<tr>
<td>HR</td>
<td>143.6 ± 20.8</td>
<td>121.6 ± 11.5*</td>
<td>118.0 ± 10.5</td>
<td>168.0 ± 14.1</td>
<td>126.8 ± 18.6*</td>
<td>128.4 ± 18.3*</td>
</tr>
<tr>
<td>RPE</td>
<td>11.2 ± 2.1</td>
<td>9.0 ± 1.2*</td>
<td>9.4 ± 3.4</td>
<td>14.6 ± 2.1</td>
<td>11.0 ± 1.4*</td>
<td>10.6 ± 3.4</td>
</tr>
<tr>
<td>SR</td>
<td>29.2 ± 3.0</td>
<td>28.6 ± 3.3*</td>
<td>-</td>
<td>34.0 ± 3.6</td>
<td>33.3 ± 3.3*</td>
<td>-</td>
</tr>
<tr>
<td>KR</td>
<td>72.7 ± 16.4</td>
<td>-</td>
<td>77.5 ± 10.6</td>
<td>87.9 ± 94.3</td>
<td>-</td>
<td>94.3 ± 15.3</td>
</tr>
</tbody>
</table>

*Significantly different to whole body swimming at the 0.05 level

Stroke rate differed between the 70% whole stroke and arms only trials (p=0.047) and the 85% whole stroke and arms only trials (p=0.032). Kick rate during the kick only trials were not different to those recorded in the whole stroke trials for either intensity. Stroke rate in the 85% whole stroke and arm stroke only trials were higher than those recorded in the 70% trials (p<0.01). Kick rate in the 85% whole stroke and kick only trials were higher than those recorded in the 70% trials (p<0.01).

Discussion

The primary aim of this study was to determine the contribution of the legs and arms to velocity in submaximal, steady-state freestyle swimming while controlling stroke and kick rate. Swimming with the arm stroke only, participants were able to achieve ~89% of the velocity achieved in the whole body trials. In contrast, swimming with the leg kick only participants achieved ~63-65% of the velocity achieved in the whole body trials. In agreement with previous research reporting the leg kick contributed ~10% to the overall swimming velocity in freestyle [1, 3], in the present study the arm stroke only trials achieved ~90% of the whole stroke velocity. It appears that this contribution holds true irrespective of the distance and velocity of the swimming trials for freestyle swimming. However, this does not account for the overlap in contributions of the legs and arms to velocity.

The secondary aim of this study was to determine the metabolic cost associated with whole stroke, arm stroke only and kick only freestyle swimming. Arm stroke swimming was found to require less energy per metre compared to the whole stroke at 85%. Leg kicking required more energy per metre than the whole stroke (p<0.05) and arm stroke swimming (p<0.001) irrespective of swimming intensity. Previous studies that have investigated the VO₂ associated with whole body, arms only and kick only swimming have reported higher relative VO₂ percentages for arm stroke only swimming when
compared to whole body swimming, e.g. 94.6% at 0.7 m·s⁻¹, 96.1% at 0.9 m·s⁻¹ [12] and 82.4% for Vo2 max [8]. Stroke rate was not reported in these studies, and thus it is possible that participants used higher stroke rates in the arms only swims compared to the whole body swims in these studies, resulting in a higher energy demand. The metabolic cost of whole body swimming for the two intensities are comparable to those reported by di Prampero [10]. When the metabolic cost was calculated, the arm stroke required the least energy per metre compared to the whole stroke and leg kick trials, even though the arm stroke trials did not have the lowest Vo2 consumption. This could imply that, when swimming with whole stroke, the legs require O2 for the muscular contractions involved with kicking, however the primary purpose of these contractions is likely to be stabilisation of the body rather than propulsion. Indeed, the swimmer achieves forward movement through the water while using the leg kick only; proving that the leg kick somewhat contributes to propulsion, however using the leg kick as a primary source of propulsion will indeed be uneconomical. These findings support the conclusions of previous authors who have suggested that high kick frequencies may in fact be counterproductive in performance terms, particularly in long distance events [2, 4, 5].

No differences in post-swim [La ] were found between whole stroke, arm stroke only and kick only, regardless of intensity. Heart rate was lower in the arms only trial compared to the whole stroke for 70% and a lower HR was also observed in the arms only and leg kick trials compared to the 85% whole stroke trial. This lower HR could be due to the lower swimming velocity, which is associated with a lower drag force and thus, a lower energy demand [9]. The difference in kick rate between whole stroke and kick only trials was not significant, suggesting the audible metronome used in this study achieved its purpose in these trials. While the stroke rates statistically differed between the whole stroke and arms only trials, the difference was small (~1 stroke per min different) and within the typical error of measurement for stroke rate [13]. As the stroke and kick rate of the arm stroke only and kick only trials were comparable to those achieved in the whole stroke trial, the internal mechanical power production during the arm stroke only and kick only trials closely replicated that of the arm stroke and the leg kick during the whole stroke trial.

This study was the first to compare the metabolic cost and velocity contributions of the upper and lower limbs to whole body swimming while aiming to control the stroke and kick rate across trials. While this is the case, swimming with the arm stroke only, the legs only and the whole stroke is no doubt associated with differences in the fluid mechanics and flow of water molecules around the body. Furthermore, the use of the pull buoy and kickboard in the arm stroke only and legs only trials may result in possible changes in the trunk angle, consequently changing the frontal surface area and active body drag. Differences in velocities across trials would also be associated with differences in drag for each trial. Therefore, the comparison of metabolic cost and velocity while swimming with the arm stroke only, legs only and whole stroke still may not represent the precise contributions of the upper and lower limbs to velocity, and future studies should aim to include measurement of the influence of the pull buoy and kickboard on the trunk angle, frontal surface area and active body drag. While limitations are evident, the control of the stroke and kick rate across trials has progressed the current understanding of the role of the arms and the legs in swimming. Future investigations aiming to identify the contributions of the arm stroke and leg kick should attempt to control the stroke and kick rate across trials. Additionally, measuring and controlling stroke length and kick depth would more accurately match the internal mechanical work demands across trials.

References

Effects of sprint interval training on metabolic, mechanical characteristics and swimming performance

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Keywords: sprint performance, metabolic capacity, drag, swimming efficiency

Abstract
This study investigated the effects of very high-intensity, low-volume, sprint interval training (SIT) on metabolic, mechanical characteristics and swimming performance. Eleven well-trained college swimmers (male n=6; female n=5; age 20±1 yrs) performed SIT twice/day, 5 days/week, for 4 weeks in swimming flume. The SIT consisted of five 5 s bouts at an intensity which cause exhaustion in around 10 s (~250%VO2max) with a 10 s rest between each bout. Before and after the training period, maximal oxygen uptake (VO2max), maximal accumulated oxygen deficit (MAOD), swimming economy, drag-swimming speed relationship and maximal propulsive power (MPP) were determined. Furthermore, a swimming record on 50m freestyle event was determined. No significant changes were found in swimming economy and drag-swimming speed relationship. On the other hand, VO2max, MAOD, and MPP increased significantly (P<0.05). Consequently, the swimming record on 50m freestyle event was significantly improved (P<0.01). These results revealed that the SIT used in this study can enhance MPP as well as VO2max and MAOD, and consequently improve sprint swimming performance even in well-trained swimmers.

Introduction
A lot of studies have reported that high-intensity or sprint interval training (SIT) can improve not only anaerobic (glycolytic) metabolism but also aerobic (oxidative) metabolism and that these metabolic adaptations cause improvements in exercise performance (Burgomaster 2006, Gibala 2008, Laursen 2002). Recently, a very high-intensity, low-volume, SIT protocol was newly developed in our laboratory, and we found that this protocol can tax simultaneously very greater stimulus (>80-90%) to
both aerobic and anaerobic energy process. Then, we hypothesised that the SIT protocol can improve very effectively metabolic capacity and consequently sprint performance. Also, swimming performance can be improved not only by an increase in metabolic capacity but also by an improved swimming technique. Therefore, present study aimed to evaluate whether the SIT can improve metabolic, mechanical characteristics, and swimming performance even in well-trained swimmers.

Methods

Subjects. The subjects were 11 well-trained college swimmers (male n=6; female n=5). Their mean (±SD) age, height, and body mass were 20(±1) yrs, 1.680(±0.040) m, and 64.0(±5.2) kg, respectively. Before volunteering, each subject was fully informed of the purposes, protocol, and procedures of this experiment, and any associated risks.

Measurements. Before and after the training period, maximal oxygen uptake (VO$_2$max), maximal accumulated oxygen deficit (MAOD), and swimming economy were measured in a swimming flume, and drag-swimming speed relationship and maximal propulsive power (MPP) were determined with measuring active drag (MAD) system. Because all subjects perform regularly VO$_2$max and drag measurement using swimming flume and MAD system, they have been fully familiarised with those tests. Furthermore, a swimming record on 50m freestyle event was also measured. The measurements at post-training were completed in a week from the end of training.

Pretest. To establish the relationship between O$_2$ demand and the exercise intensity for each subject, steady-state VO$_2$ during a 6 min swimming at a constant water flow rate was determined, and VO$_2$ was measured during the last 2 minutes of each measurement. The 6 min swimming was performed intermittently at 8 or more different water flow rates below VO$_2$max. The water flow rate was increased by 0.03–0.05 m · s$^{-1}$. The subjects were allowed adequate rest between bouts. In this experiment, the cube of water flow rate was used as an indicator of the exercise intensity during swimming because it has been revealed that the power to overcome drag during swimming increases with the cube of the velocity. Actually, several studies have shown that VO$_2$ increases linearly with the cube of water flow rate (Ogita 1996, Ogita 1999).

In this experiment, VO$_2$ was determined by the Douglas bag method. The O$_2$ and CO$_2$ fraction in the expired gas were determined by an automatic gas analyzer (Vmax 29, Sensormedics Corporation, California, USA). Expired gas volume was measured by a dry gas meter.

VO$_2$max and MAOD. After the linear relationship between O$_2$ demand and exercise intensity was determined for each subject, VO$_2$ during several bouts of swimming at higher water flow rates was measured. VO$_2$max was determined by the leveling-off criterion and a leveling-off of VO$_2$ was observed in all swimmers.

MAOD was determined during a supramaximal swimming lasting 2-3 min. Several investigations have shown that the accumulated O$_2$ deficit reaches plateau during exhaustive exercise over 2 min (Medbø 1988, Ogita 2003). The O$_2$ demand of the exhausting bout was estimated individually by extrapolating the linear relationship between O$_2$ demand and exercise intensity (i.e. the cube of water flow rate). Water flow rate was pre-determined on pretests. Accumulated oxygen demand was taken as the product of the estimated O$_2$ demand at the exercise intensity and the exercise duration. The accumulated O$_2$ deficit was calculated by the accumulated O$_2$ demand minus the accumulated O$_2$ uptake.

Swimming economy. In five of eleven subjects, swimming economy was determined as VO$_2$ which was measured during swimming at a water flow rate corresponding to 70% VO$_2$max at pre-test.

Active drag and MPP. All mechanical analyses were completed with a modified MAD system similar to that described by Toussaint et al. (1988) (Figure 1). The essential aspects of the apparatus and the accuracy of the collected data have been previously described in detail (Toussaint 1988). The system allowed the swimmer to push off from fixed pads at each stroke. The 15 push-off pads were fixed 1.30
m apart on 23 m horizontal rods, and the rods were mounted 0.75m below the water surface. The rod was instrumented with a force transducer at one end of swimming pool to measure the push-off forces. The force signal was low-pass filtered (30-Hz cut-off frequency), on-line digitised at 100-Hz sampling rate, and stored on the hard disk of notebook computer. The force signal pushed off from the second to the last (15th) pad was time integrated, and yielded the average force. The mean velocity was computed from the time taken to cover the distance between the second and last pad (i.e.13 x 1.3 = 16.9 m). For the drag measurement, the subject performed only arm stroke (without leg kicking), and their legs were supported and fixed together by the same pull buoy (Arena ARN-100).

![Figure 1](image)

**Figure 1**  Schematic side view of system to measure active drag (MAD system) used in this study

To determine drag-swimming speed relationship, the subjects were asked to swim 25 m more than 10 times at different but constant velocity (range 0.80-1.90 m•s\(^{-1}\)). At constant swimming velocity, it can be recognised that the mean propulsive force is equal to the mean drag force \(F_d\) (Toussaint 1988b). On each trial, mean \(F_d\) and mean swimming velocity \(v\) were calculated. These \(v\) and \(F_d\) data were least-squares fitted to the function:

\[
F_d = A \cdot v^n
\]

Where, \(A\) and \(n\) are constants of proportionality, and were respectively adopted as drag coefficient and drag exponent in this study. Propulsive power was calculated by the product of \(F_d\) and \(v\), and the highest value was accepted as maximal propulsive power (MPP).

**Sprint performance.** To evaluate the effect on sprint swimming performance, a swimming record on 50m freestyle event was determined. The record was measured using stopwatch by three examiners, and the average of three records was adopted.

**Training.** The protocol of the SIT consisted five x 5 s bouts at an intensity which cause exhaustion in around 10 s (~250%VO\(_{2}\)max), and each bout was separated by 10-s rest. The SIT was performed twice a day, 5 days a week, for 4 weeks using front crawl in a swimming flume, and twice-daily SIT was separated by 20 min rest.

**Statistics.** The results are shown as means ± SD. Differences of the responses between pre- and post-training were tested by a paired Student’s t-test. Results were regarded as statistically significant if \(P<0.05\).

**Results**

**VO\(_{2}\)max, MAOD and swimming economy.** After 4 weeks of training, VO\(_{2}\)max (\(P<0.05\)) and MAOD (\(P<0.01\)) significantly increased by 5% and 22%, respectively, whereas swimming economy did not change compared to the value at pre-training.

**Drag-swimming speed relationship and MPP.** Neither \(A\) (drag coefficient) nor \(n\) (drag exponent) changed significantly after the training, and thus drag-swimming speed relationship in pre- and post-training was quite comparable. However, MPP significantly increased by 9% (\(P<0.05\)).
**Table 1** Comparison of VO2max, MAOD, swimming economy, drag coefficient, drag exponent, MPP, and 50m sprint event between pre- and post-training

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th>Post</th>
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<tbody>
<tr>
<td>VO2max (l•min⁻¹)</td>
<td>3.43 ± 0.7</td>
<td>3.59 ± 0.76</td>
</tr>
<tr>
<td>MAOD (l)</td>
<td>55.0 ± 6.6</td>
<td>57.5 ± 7.0</td>
</tr>
<tr>
<td>swim economy (l•min⁻¹)</td>
<td>2.51 ± 0.46</td>
<td>2.53 ± 0.47</td>
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<tr>
<td>drag coefficient</td>
<td>21.8 ± 5.1</td>
<td>21.9 ± 4.1</td>
</tr>
<tr>
<td>drag exponent</td>
<td>2.07 ± 0.14</td>
<td>2.07 ± 0.08</td>
</tr>
<tr>
<td>MPP (w)</td>
<td>118 ± 51</td>
<td>129 ± 50</td>
</tr>
<tr>
<td>50m time (s)</td>
<td>26.60 ± 1.91</td>
<td>26.18 ± 1.75</td>
</tr>
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Significant differences are indicated by the following: ** P<0.01 * P<0.05

VO2max; maximal oxygen uptake, MAOD; maximal accumulated oxygen deficit MPP; maximal proplusive power

**Sprint performance.** The swimming record on 50m freestyle event was significantly improved by 0.42 s after the training (P<0.01).

**Discussion**

This study examined the effects of very high-intensity, low-volume, SIT on metabolic, mechanical characteristics and swimming performance. The main findings were that the SIT could improve metabolic capacity, MPP and consequently sprint swimming performance only in 4 weeks even in well-trained swimmers, but did not change any technical factors such as drag-swimming speed relationship and swimming economy.

Swimming performance is determined by the function of metabolic capacity, drag and swimming efficiency. In competitive swimming event, the difference between win and loss is sometimes within 0.1 s. Therefore, a small reduction in drag would be very important for swimmers to improve their performance. Actually, from 2008 to 2009, numerous new world records were made in competitive swimming races. Since swimwear developed in those days could bring a drag reduction effect of 2-6% (but not statistically significant) (Ogita 2010), the great success have been considered to be in part attributed to a reduction in drag associated with advance in quality of swimwear (or suit). However, in this experiment, no significant changes were found in both drag coefficient and exponent, and consequently, drag-swimming speed relationship. Therefore, the improvement of sprint performance is not responsible for the reduction in drag.

The submaximal VO₂ determined as swimming economy were quite comparable between pre- and post-training. Furthermore, as previously mentioned, no significant difference was observed in drag-swimming speed relationship between pre- and post-training. This means that neither mechanical power output nor the rate of energy expenditure in relation to swimming speed changed, and thus, it implies that swimming efficiency would remain unchanged. Therefore, it is considered that the better swimming performance after the SIT would not be attributed to improvement of swimming efficiency, either.

Because swimming performance is determined by the function of metabolic capacity, drag and swimming efficiency, as long as drag-swimming speed relationship and swimming efficiency are kept constant, the improvement of swimming performance depends on the increase in metabolic capacity. Especially, the relative contribution of anaerobic energy process for exhaustive swimming lasting ~30s is around 70% or more (Ogita 2003). Therefore, it should be a great advantage for improving sprint swimming performance to enhance MAOD as anaerobic capacity. In this study, large increase (22%) in MAOD was found after the training. Furthermore, MPP increased significantly around 10%. Taken together, the improvement of 50 m swimming performance would be strongly attributed to the increase in MPP associated with the enhanced anaerobic capacity.
In addition, VO$_2$max also increased significantly after the training although it was only 6%. In the last decade, a lot of investigations have also reported the evidences that high-intensity interval training or SIT can improve not only anaerobic but also aerobic metabolism such as increase in activities of mitochondrial enzymes and VO$_2$max (Burgomaster 2006, Gibala 2008, Laursen 2002). However, SIT used in this experiment is very high-intensity and low-volume, which consisted only five x 5 s bouts with 10 s rest. In our knowledge, this is the smallest training volume when compared to those of previous studies.

It must be a quite notable finding that both anaerobic capacity and VO$_2$max and consequently swimming performance was improved within only 4 weeks even in the well-trained swimmers. It has been suggested that the greater stimulus to aimed energy system, the larger improvement of metabolic capacity (Fox 1975). In the pretest, we confirmed that VO$_2$ during 5th 5 s bout of the SIT protocol reached ~96% VO$_2$max and that the accumulated O$_2$ deficit during SIT corresponded to ~80% of anaerobic capacity (unpublished data). This implies that the protocol of SIT can give strong enough stimulus to improve both anaerobic and aerobic metabolism even though it is very low volume. Also, our results that swimming performance can be improved within very short period even in well-trained swimmers if appropriate stimulus can be taxed to anaerobic and aerobic energy system.

**Conclusion**

Our results revealed that high-intensity, low-volume, SIT used in this study can improve MPP associated with an increase in metabolic capacity as VO$_2$max and MAOD, and consequently sprint swimming performance. However, there was no affect on swimming economy and the drag-swimming velocity relationship.

**References**


Changes in heart rate during headstand in water

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Keywords: heart rate, headstand, in water, diving reflex, venous return

Abstract

A previous study showed that heart rate (HR) significantly decreased during standing while in water, and that the phenomenon depended on the depth of immersion. A headstand posture is often assumed during synchronised swimming. However, it is uncertain whether changes in HR during a headstand position in water are the same as those while in a standing position. In this study, we determined the changes in HR during a headstand posture in water. Ten healthy Japanese males volunteered for this study and provided their informed consent prior to their participation. Measurements were conducted under two conditions, on land and in water, in a random order. Each subject maintained a headstand position on land or in a swimming pool for one min. While in water, the subjects breathed through a compressed gas cylinder used for scuba diving. Water depth was set at a subject’s waist level. Water and room temperatures were maintained at 30°C and 28°C, respectively. HR was continuously measured using a waterproof HR monitor. HR rapidly decreased within 18 seconds from the beginning of a headstand posture while in water and was subsequently maintained at a steady state. The changes in HR while in the water were statistically significant interaction (by Repeated two-way ANOVA, p < 0.05). By comparison, HR responses while on land decreased until 18 seconds and then showed a minimal increase. HR when in water (55 ± 5 bpm) was significantly lower than when on land (68 ± 7 bpm; p < 0.05). Our results showed that HR decreased during a headstand while in water, which could be attributed to the diving reflex and an increase in venous return.

Introduction

During water exercise, it has been established that heart rate (HR), oxygen uptake, and body temperature respond to the effects of the physical characteristics of water (water pressure, temperature, buoyancy and viscosity)6,8,10,17,18, 23,26,28,29. Previous studies have demonstrated that these responses differed from those while on land due to the physical characteristics of water1,5, 7,9,15, 16, 25,29, 30. One study showed that HR significantly decreased during standing in water, and that the decreased HR depended on the depth of immersion14,19. This could quicken the venous return by acting on the water pressure to veins and would increase the stroke volume and decrease the HR20.

Another previous study established a relationship between HR and body posture11,12. HR significantly decreased during standing in water. A headstand posture is often assumed during synchronised swimming at swimming competitions. However, it remains uncertain whether changes in HR while in a headstand position in water are the same as those while in a standing position. We hypothesised that HR would decrease during a headstand while in water. Thus, the purpose of this study was to determine the changes in HR during a headstand posture while in water.

Methods

We recruited ten healthy male Japanese volunteers for this study. Their mean age was 23 ± 3 years, mean height was 173 ± 6 cm and mean body weight was 70 ± 6 kg. All subjects gave their written informed consent before their enrolment. This study was approved by the Ethics Committee of
Kawasaki University of Medical Welfare (Japan). Our study protocol was in accordance with the Declaration of Helsinki. None of the subjects smoked or had medical histories, including metabolic diseases, which may have affected the cardiovascular system. The subjects were instructed to refrain from consuming caffeine and alcohol and performing high-intensity exercises for two days before the experiment to control for withdrawal or the acute effects of these drugs and exercise on our primary outcome measures.

Each subject performed a headstand for one minute under each condition. Measurements were made under two conditions: A, headstand on land; and B, headstand in water. These were done in a random order. Each subject maintained a headstand position on land or in a swimming pool for one min; while in the water, each subject breathed through a compressed gas cylinder used for scuba diving. Water depth was set at the waist (navel) level during standing in water, and the same water depth was used during a headstand\textsuperscript{2,19}.

Water and room temperatures were maintained at 30°C and 28°C, respectively. HR was continuously measured using a waterproof HR monitor (MemCalc/Bonaly Light; BMS, Japan).

The data was presented as mean ± standard deviation. The response of heart rate was analyzed by two-way (condition×time) ANOVA of repeated measures. In the case of significant F-values, a post hoc test (Bonferroni) was used to identify significant differences among mean values. Statistical significance level was set at \( p<0.05 \). The data was analyzed by SPSS ver. 12.0 for Windows.

**Results**

Fig. 1 shows the changes in HR under condition A and condition B. HR rapidly decreased within 24 s from the beginning of a headstand posture while in water (condition B) and subsequently maintained a steady-state level. The changes in HR while in water (condition B) were statistically significant (by ANOVA, \( p<0.05 \)). By comparison, HR responses under condition C decreased until 18 seconds and then minimally increased through the remainder of the measurement period. The mean HR under condition D (55 ± 5 bpm) was significantly lower than that under condition C (68 ± 7 bpm; \( p<0.05 \)).
Note: values are means ± SD’s. * significant difference between condition A and condition B; p < 0.05.

Figure 1 Changes in heart rate in the headstand position on land (condition A: ■) and in water (condition B: □)

Discussion

We will discuss our results based on three considerations: venous return\(^{20,21,22}\), the diving reflex\(^{4,10,26,27}\), and exercise intensity\(^{5,9,15,20,23}\). HR during water immersion is lower than when on land, and this decrease in HR could depend on the water level\(^{11,12}\). This could quicken the venous return by acting on the water pressure to veins and thus, would increase the stroke volume and decrease the HR\(^{21,22}\). This, in turn, could cause the transfer of cellular fluids from tissues to blood vessels, because the working hydraulic pressure is 0.1 atmospheres while in water\(^{17,18}\). The transfer of cellular fluids could enhance venous return and cause an increase in central cardiovascular volume\(^{20,22}\) and could also increase the volume of venous return, which would cause an increase in cardiac output\(^{22}\). A decreased HR during water immersion is primarily due to the greater venous return-associated increase in cardiac output.

These phenomena could occur within approximately 20 seconds after immersion, and a delay in observing this phenomenon could depend on the water level\(^{21,22}\). We consider that the time order for the changes in HR that we observed agreed with that in a previous study\(^{21}\). The changes in HR until 18 seconds followed a similar time course with both conditions. Therefore, we consider that a decrease in HR until 18 seconds was caused by the change in posture and those changes after 18 seconds were caused by the acceleration of venous return.

The other factor for a decrease in HR under condition B could be due to the effect of the diving reflex\(^{4,10,26,27}\). The diving reflex results in a decrease in HR during facial immersion. Humans and other animals are known to have a diving reflex\(^{4,27}\). HR in men decreased until approximately 60 seconds during apnea with immersion in water. However, in the present study, HR remained at steady state after 30s under condition B. We consider that our subjects were affected by breathing through a compressed gas cylinder used for scuba diving while in the water.
A change in load weight could also depend on the water level. According to Archimedes’ principle, when the water level is increased, body buoyancy is increased\textsuperscript{17,18}. This suggests that exercise intensity was very low during our condition B, and that the change in venous return volume could maintain this acceleration\textsuperscript{20}. Consequently, we consider that the HR decrease during a headstand while in water could combine with these three mechanical functions.

**Conclusion**

Our results showed that HR decreased during a headstand while in water, which could be attributed to the diving reflex and an increase in venous return.

**References**


Are different methods for the aerobic capacity evaluation providing coherent biomechanical parameters?

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Keywords: oxygen uptake, biomechanical parameters, aerobic capacity evaluation, swimming training

Abstract

Introduction. Monitoring the swimming training process requires reliable methods for aerobic capacity evaluation. There are different methods available in literature, eventually providing similar feedback regarding swimming velocity and blood [La-]. Nevertheless, a given swimming velocity can be achieved through different stroke rate and stroke length relationship. Indeed, different
adjustments in the biomechanical parameters can interfere with swimming efficiency, which is a major determining factor of swimming performance. Thus, for training prescription, it is important to determine the best individual swimming velocity for aerobic capacity potentiation, but also the biomechanical determining factors characteristic of that particular intensity. Therefore, this study aimed to compare swimming biomechanical parameters and velocity (v) obtained by the gold-standard method, i.e. the maximal lactate steady state test (MLSS), and those obtained from the main and most common methods employed to evaluate aerobic capacity in swimming training.

Methods. Five elite female swimmers (17.2 ± 2.3 yrs, 1.68 ± 0.04 m, 61.4 ± 5.0 kg) performed in different days: 1) an intermittent incremental protocol until voluntary exhaustion to determine the v associated to the individual lactate threshold (IAT), ventilatory threshold (VT), heart rate threshold (HRT), lactate threshold of fixed 3.5 mmol.L⁻¹ (LT3.5) and maximal oxygen uptake (VO₂max) (Fernandes et al. 2006); 2) two to three 30min sub-maximal continuous tests to determine the v associated to the MLSS (Pellarigo et al. 2011). Swimming velocity, blood lactate concentration ([La⁻]), stroke rate (SR), stroke length, (SL) and stroke index (SI) were controlled during all the tests. ANOVA repeated measures and regression analysis were performed to test differences between the methods (p < 0.05).

Results. The findings revealed that v at the LT3.5 test was higher (1.32 ± 0.08 m.s⁻¹) compared to MLSS, IAT, VT and HRT (1.24 ± 0.09, 1.24 ± 0.06, 1.23 ± 0.06 and 1.25 ± 0.06 m.s⁻¹, respectively). SR was higher during the LT3.5 (35.8 ± 2.2 cycles.min⁻¹) compared to IAT, VT and HRT (32.2 ± 1.5, 31.8 ± 1.0 and 32.3 ± 1.6 cycles.min⁻¹, respectively). However, SR was similar compared to MLSS (34.1 ± 3.0 cycles.min⁻¹). SL at the MLSS (2.18 ± 0.10 m.cycle⁻¹) and LT3.5 (2.22 ± 0.11 m.cycle⁻¹) were lower compared to IAT, VT and HRT (2.31 ± 0.09, 2.32 ± 0.08 and 2.31 ± 0.09 m.cycle⁻¹, respectively). SI was lower during the MLSS (2.71 ± 0.23) compared to IAT, VT, HRT and LT3.5 (2.87 ± 0.21, 2.86 ± 0.21, 2.89 ± 0.20 and 2.93 ± 0.27, respectively). The percentage of SR and SL at MLSS regarding to the VO₂max were 89.4 ± 7.0 and 103.2 ± 8.1%, respectively. Furthermore, high correlation values were obtained between MLSS/IAT and MLSS/VT (p < 0.05).

Conclusions. These findings suggest that IAT and VT may be better predictors of the gold-standard method for the aerobic capacity evaluation compared to LT3.5 and HRT.

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Keywords: biomechanical parameters, aerobic capacity evaluation, swimming training

Introduction

To attain the best performance in swimming, technique is as important as the physiological support of exercise. Generally, the increase of v is obtained by an increase of propelling efficiency and/or by a decrease of drag forces (Toussaint & Hollander 1994). Therefore, the level of swim technique can be expressed by the capacity to reduce hydrodynamic drag (Hollander et al. 1986; Kolmogorov & Duplischcheva 1992) and to enhance the propulsive force (Rouard, Schleihauf & Troup 1996; Schleihauf et al. 1988).

The most important methods, i.e. reliable and useful methods, to evaluate and prescribe the swim aerobic training intensity have been used by researchers and coaches, and are commonly considered as methods of physiologic evaluation. However, the swim performance at a given physiologic intensity is not only highly dependent on the physiological aspects, but is also related to the biomechanical parameters such as the combination of stroke rate (SR) and stroke length (SL) for a given intensity or velocity (Craig & Pendergast 1979).

Thereby, the purpose of the study was to compare the biomechanical parameters and the v obtained by the gold-standard method, i.e. the maximal lactate steady state test (MLSS), to the other main methods employed to evaluate aerobic capacity in swimming.
Methods

Five elite female endurance swimmers (17.2 ± 2.3 yrs, 1.68 ± 0.04 m, 61.4 ± 5.0 kg and 15.3 ± 3.1% body fat mass) volunteered for this study, and signed an informed consent before participation. The swimmers had at least seven years of experience as competitive swimmers and a mean performance over a 400 m freestyle swim of 87.9 ± 3.1% of the short course word record. Tests were performed in a 25 m indoor swimming pool. The swimmers used in-water starts and open turns without underwater gliding. All the tests were conducted in three to four days, at the same time of the day (± 2h) to minimise the effect of circadian variation during the tests (Atkinson & Reilly 1996). The swimmers were advised to avoid high intense training during the 24 h before experimental sessions. A 1000 m warm-up at moderate aerobic intensity was performed.

Swimmers performed a front crawl intermittent incremental swimming protocol (n x 200 m, increments of 0.05 m.s^{-1} and 30 s rest intervals between each step) until voluntary exhaustion (Cardoso et al. 2003; Fernandes et al. 2006). Subsequently, they performed two to three 30 min submaximal constant tests at imposed paces for the assessment of swimming v associated to the MLSS (Pelarigo, Denadai & Greco 2011). The MLSS v was defined as the highest velocity at which the [La-] did not increase more than 1mmol.L^{-1} between the 10th and 30th swim minute.

Earlobe capillary blood samples were collected: 1) at rest, at the end of each intermediate step of the incremental test during the 30 s interval, and immediately after and at each 2 min of recovery the last step, until the [La-] recovery peak was found; 2) at rest, at the 10th and 30th min (or voluntary exhaustion) of each continuous swimming test to assess [La-]. The corresponding [La-] was calculated as the average of the two [La-] values obtained at the 10th and the 30th minutes (Heck, Mader & Hess 1985). Capillary [La-] was assessed through a portable lactate analyzer (Lactate Pro, Arkray, Inc.).

The control of swimming v was performed using a visual underwater pacer on the bottom of the pool (GBK-Pacer, GBK Eletronics, Aveiro, Portugal) to control the predetermined imposed v. It was considered that exhaustion was reached, and also the end of the test, when the swimmers remained 5 m behind the light, incapable to follow the prescribed pace.

The incremental test was performed to determine the v values prescribed by the main methods commonly used for the evaluation of the aerobic capacity and the maximal oxygen uptake (VO_{2,max}). Consequently, all the corresponding values of biomechanical parameters were determined through interpolation based on a polynomial regression model calculated between the incremental velocities and their corresponding parameters (Neter, Wasserman & Kutner 1985).

The IA nT was calculated through the mathematical modelling method proposed by (Machado, Almeida, Morais, Fernandes & Vilas-Boas 2006). The LT3.5 was determined through the fixed 3.5mmol.L^{-1} value of [La-] and its corresponding v (Heck, et al. 1985). The VT was determined using the v slope method and its respective values of pulmonary ventilation (V_{l}) divided by the oxygen uptake (V_{E}.VO_{2})^{-1}, defining a disproportional increase of ventilation concerning the increase at speed of locomotion during an incremental exercise test (Svedahl & MacIntosh 2003). The HRT was calculated through the curve slope method calculated between v and heart rate (Cellini et al. 1986), assuming that the inflection point of the curve corresponds to the HRTv.

The biomechanical parameters were measured by an overwater video camera operating at a frequency of 50 Hz, allowing to analyse two stroke cycles in the middle of the pool. The SR was determined by the number of cycles per unit of time (cycles.min^{-1}), the SL (m.cycle^{-1}) by the ratio of v (m.s^{-1}) and the SR, and the SI was the product of v and SL. The biomechanical parameters were assessed in each 50 m of each intensity of the incremental test, and averaged for the entire step. The MLSS test was splited into seven time moments corresponding to the 4th min, 25, 33, 50, 66, 75, and 100% of the total MLSS duration; biomechanical parameters were assessed during the last 1 min of each test phase to calculate the mean. The mean values of all test pahses were obtained and assumed as the parameter’s values.
Data are presented as mean (±SD) and their corresponding 95% confidence intervals ([95%CI]). All the statistical assumptions were checked before the analysis. The one-way ANOVA for repeated measures was conducted to compare the swimming v and biomechanical parameters between aerobic capacity assessment methods, complemented with Bonferroni correction and post-hoc test. The partial Eta square ($\eta_p^2$) was used to measure the effect size, in which was defined as small, medium and large for values of 0.01, 0.06 and 0.14, respectively (Stevens 2002). The regression analysis was performed using Passing & Bablok regression (MedCalc Statistical Software, Belgium) to compare the MLSS with other methods regarding the v and biomechanical parameters, and their corresponding 95% confidence intervals (95% CI) to determine the degree of association between the methods. The Pearson’s coefficient of determination ($R^2$) was used. It was accept a 5% significance level ($p < 0.05$).

**Results**

Results showed close relationship (high $R^2$ values) and non-statistical significant differences between the v values obtained for the critical intensity to aerobic capacity training considering MLSS, IAnT, VT and HRT assessment methods. The LT3.5$v$ was higher compared to all other methods ($F_{4,16} = 7.106, p = 0.002, \eta_p^2 = 0.640$). The SR values were similar comparing the MLSS to the other methods. Contrary, the LT3.5 was higher than IAnT, VT and HRT values ($F_{4,16} = 8.069, p = 0.001, \eta_p^2 = 0.669$). The SL values were similar comparing the MLSS to the LT3.5; however, these methods showed lower values compared to IAnT, VT and HRT ($F_{4,16} = 10.020, p = 0.000, \eta_p^2 = 0.715$). The SI at MLSS was lower comparing to the corresponding values obtained by the other methods ($F_{4,16} = 8.122, p = 0.001, \eta_p^2 = 0.670$).

The percentual of SR values at maximal oxygen uptake (%SRV$O_{2\text{max}}$), was similar among the MLSS, IAnT, VT and HRT. On the other hand, the corresponding value obtained for LT3.5 was higher than IAnT, VT and HRT values ($F_{4,16} = 8.693, p = 0.001, \eta_p^2 = 0.685$). The percentual of SL values at maximal oxygen uptake (%SLV$O_{2\text{max}}$) showed similar values between MLSS and LT3.5, whereas these methods showed lower %SLV$O_{2\text{max}}$ compared to IAnT, VT and HRT corresponding values ($F_{4,16} = 9.300, p = 0.000, \eta_p^2 = 0.699$) (Table 1).

**Table 1** The velocity and biomechanical parameters compared between the main methods for the aerobic capacity evaluation in swimming (n=5)

<table>
<thead>
<tr>
<th></th>
<th>MLSS</th>
<th>IAnT</th>
<th>VT</th>
<th>HRT</th>
<th>LT3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>v (m.s$^{-1}$)</td>
<td>1.24 (0.09)</td>
<td>1.24 (0.06)</td>
<td>1.23 (0.06)</td>
<td>1.25 (0.06)</td>
<td>1.32 (0.08)$^{1,2,3,4}$</td>
</tr>
<tr>
<td></td>
<td>[1.13 to 1.35]</td>
<td>[1.17 to 1.31]</td>
<td>[1.16 to 1.30]</td>
<td>[1.18 to 1.32]</td>
<td>[1.22 to 1.42]</td>
</tr>
<tr>
<td>SR (cycles.min$^{-1}$)</td>
<td>34.1 (3.0)</td>
<td>32.2 (1.5)</td>
<td>31.8 (1.0)</td>
<td>32.3 (1.6)</td>
<td>35.8 (2.2)$^{3,4}$</td>
</tr>
<tr>
<td></td>
<td>[30.4 to 37.9]</td>
<td>[30.3 to 34.0]</td>
<td>[30.6 to 33.0]</td>
<td>[30.4 to 34.3]</td>
<td>[33.1 to 38.5]</td>
</tr>
<tr>
<td>SL (m.cycle$^{-1}$)</td>
<td>2.18 (0.10)$^{2,3,4}$</td>
<td>2.31 (0.09)</td>
<td>2.32 (0.08)</td>
<td>2.31 (0.09)</td>
<td>2.22 (0.11)$^{3,4}$</td>
</tr>
<tr>
<td></td>
<td>[2.07 to 2.30]</td>
<td>[2.20 to 2.43]</td>
<td>[2.23 to 2.42]</td>
<td>[2.20 to 2.43]</td>
<td>[2.08 to 2.36]</td>
</tr>
<tr>
<td>SI</td>
<td>2.71 (0.23)$^{2,3,4,5}$</td>
<td>2.87 (0.21)</td>
<td>2.86 (0.21)</td>
<td>2.89 (0.20)</td>
<td>2.93 (0.27)</td>
</tr>
<tr>
<td></td>
<td>[2.42 to 3.00]</td>
<td>[2.60 to 3.13]</td>
<td>[2.60 to 3.13]</td>
<td>[2.64 to 3.14]</td>
<td>[2.60 to 3.26]</td>
</tr>
<tr>
<td>%SRV$O_{2\text{max}}$ (%)</td>
<td>89.4 (7.0)</td>
<td>84.2 (2.2)</td>
<td>83.3 (2.7)</td>
<td>84.7 (4.8)</td>
<td>93.7 (3.7)$^{3,4}$</td>
</tr>
<tr>
<td></td>
<td>[80.7 to 98.0]</td>
<td>[81.4 to 86.9]</td>
<td>[79.9 to 86.6]</td>
<td>[78.7 to 90.7]</td>
<td>[89.1 to 98.2]</td>
</tr>
<tr>
<td>%SLV$O_{2\text{max}}$ (%)</td>
<td>103.2 (8.1)$^{2,3,4}$</td>
<td>109.1 (5.1)</td>
<td>109.6 (5.7)</td>
<td>109.2 (5.7)</td>
<td>104.5 (3.8)$^{3,4}$</td>
</tr>
<tr>
<td></td>
<td>[93.1 to 113.2]</td>
<td>[102.7 to 115.4]</td>
<td>[102.6 to 116.6]</td>
<td>[102.1 to 116.2]</td>
<td>[99.8 to 109.2]</td>
</tr>
</tbody>
</table>

$^{1,2,3,4}$ Statistical different from MLSS, IAnT, VT, HRT and LT3.5, respectively ($p < 0.05$).

The $R^2$ values and the Passing & Bablok regression equation parameters (Slope B and Intercept A) of the v and biomechanical parameters measured between MLSS and IAnT, MLSS and VT, MLSS and HRT, and MLSS and LT3.5 are presented in Table 2.
Table 2  Agreement values of \( \nu \) and biomechanical parameters obtained between MLSS vs IAnT, MLSS vs VT, MLSS vs HRT and MLSS vs LT3.5 assessed by Passing & Bablok regression analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>MLSS vs IAnT</th>
<th>MLSS vs VT</th>
<th>MLSS vs HRT</th>
<th>MLSS vs LT3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu ) (m.s(^{-1}))</td>
<td>0.940*</td>
<td>0.876*</td>
<td>0.364</td>
<td>0.759*</td>
</tr>
<tr>
<td></td>
<td>0.620 (0.144 to 1.160)</td>
<td>0.558 (-0.048 to 2.363)</td>
<td>0.551</td>
<td>0.876</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.048 (0.148 to 1.585)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR (cycles.min(^{-1}))</td>
<td>0.674</td>
<td>0.930*</td>
<td>0.284</td>
<td>0.307</td>
</tr>
<tr>
<td></td>
<td>0.316 (-0.000 to 11.981)</td>
<td>0.316 (-0.000 to 11.981)</td>
<td>0.783</td>
<td>0.361</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.783</td>
<td></td>
</tr>
<tr>
<td>SL (m-cycle(^{-1}))</td>
<td>0.487</td>
<td>0.486</td>
<td>0.533</td>
<td>0.155</td>
</tr>
<tr>
<td></td>
<td>0.783</td>
<td>0.783</td>
<td>0.979</td>
<td>1.432</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>0.915*</td>
<td>0.892*</td>
<td>0.583</td>
<td>0.728</td>
</tr>
<tr>
<td></td>
<td>0.908 (-0.195 to 2.804)</td>
<td>0.908 (-0.195 to 2.804)</td>
<td>-0.365</td>
<td>1.124</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% SR VO(_{2\text{max}}) (%)</td>
<td>0.866*</td>
<td>0.542</td>
<td>0.235</td>
<td>0.918*</td>
</tr>
<tr>
<td></td>
<td>0.333</td>
<td>0.222</td>
<td>0.800</td>
<td>0.697 (-0.333 to 2.000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.800</td>
<td></td>
</tr>
<tr>
<td>% SL VO(_{2\text{max}}) (%)</td>
<td>0.939*</td>
<td>0.876*</td>
<td>0.092</td>
<td>0.618</td>
</tr>
<tr>
<td></td>
<td>0.604 (-0.333 to 3.000)</td>
<td>0.682</td>
<td>0.481</td>
<td>0.432 (-0.667 to 7.000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Coefficient of determination (\( R^2 \)) and regression equation variables are presented.

* \( p < 0.05; \)

Highly correlated (\( p < 0.05 \)) \( \nu \) values were obtained between MLSS-IAnT, MLSS-VT and MLSS-LT3.5. Also highly correlated SR values were observed of MLSS-VT, and the SI between MLSS-IAnT and MLSS-VT. Again, highly correlated %SRVO\(_{2\text{max}}\) values were obtained between MLSS-IAnT, and SLVO\(_{2\text{max}}\) between MLSS-IAnT, MLSS-VT and MLSS-HRT. The Passing & Bablok regression analysis of the \( \nu \) values obtained between MLSS and IAnT, MLSS and VT, MLSS and HRT, and MLSS and LT3.5 are shown in Figure 1.
Discussion

This study aimed to compare the $v$ and biomechanical parameters regarding the main evaluation methods used by researchers and coaches around the world to control and prescribe the aerobic capacity training in swimming. We compared the most well-known methods with the MLSS, considered as the gold-standard method for the aerobic capacity evaluation. The main findings suggest that the IAnT and VT tests are the better predictors of the MLSS test concerning the swimming intensity ($v$). However, the analysis of the biomechanical parameters showed that only the SR values obtained during the VT test were statistical significant and highly correlated to the MLSS test, suggesting that this might be the test with closest output regarding the chosen gold standard.

The IAnT and VT tests did not present significant differences with the MLSS test regarding the velocity, as well as high agreement were obtained using regression analysis. These results were similar to those reported in literature, in which they did not find significant differences between the IAnT (1.10 m.s$^{-1}$) and MLSS (1.09 m.s$^{-1}$) in swimming (Fernandes, Sousa, Machado & Vilas-Boas 2011), and between the VT (302 W) and MLSS (311 W) in cycling (Van Schuylenbergh, Vanden Eynde & Hespel 2004).

The MLSS and HRT intensities were similar (1.24 and 1.25 m.s$^{-1}$, respectively). However, when the regression analysis was considered, the variables presented lower correlation ($R^2 = 0.364$), corroborating the literature that considers the HRT as not possible capable to precisely predict MLSS (Van Schuylenbergh et al. 2004). Conversely, the comparison of MLSS to LT3.5 intensities showed significantly different swimming velocities (1.24 and 1.32 m.s$^{-1}$, respectively), such as previously stated in the literature (Fernandes et al. 2011). However, these methods presented high correlation using regression analysis ($R^2 = 0.759$), showing that LT3.5 has some potential for quantitative evaluation, but not for training prescription.

![Figure 1](image1.png)  
Figure 1  Passing-Bablok regression analysis of $v$ values obtained during MLSS vs LT (upper left panel), MLSS vs VT (upper right panel), MLSS vs HRT (lower left panel), and MLSS vs LT3.5 (lower right panel) methods ($n=5$)
The SR presented similar values comparing the MLSS to the other methods, although the LT3.5 was higher compared to IAnT, VT and HRT methods. However, a high agreement was only obtained between MLSS and VT tests ($R^2 = 0.930$). The SR obtained during the MLSS presented in this study corroborate the values obtained at the maximal speed of 30 min, method that have been used as predictor of the MLSS (Greco, Pelarigo, Figueira & Denadai 2007).

Concerning the SL, the MLSS presented similar values compared to LT3.5, while the MLSS was lower than IAnT, VT and HRT. These SL values obtained during the MLSS corroborate the literature (Oliveira, Caputo, Dekerle, Denadai & Greco 2012). However, none of the studied methods demonstrated high correlation compared to the gold-standard method during the regression analysis. It seems that the SL may be more sensible to specificities between continuous/rectangular and intermittent/incremental exercise, in which the characteristic pauses of the intermittent exercise may improve the lactate removal and the restoration of creatine phosphate (Billat 2001), allowing the swimmers to maintain higher SL values for a given intensity compared to the MLSS test.

Additionally, the SI value obtained during the MLSS was lower compared to the other methods, whereas the IAnT and VT presented high correlations values ($R^2 = 0.915$ and $R^2 = 0.892$, respectively) with the MLSS. Moreover, once the SI has been considered as an index of swimming efficiency, differences observed between continuous and intermittent tests may suggest that intermittent protocols may allow higher values of swimming efficiency.

Thereby, these findings suggest that IAnT and VT tests may be the better predictors of the gold-standard method for the aerobic capacity training intensity evaluation, when compared to the LT3.5 and HRT. However, the biomechanical parameters seem to present different adjustments determined by the exercise mode (continuous vs intermittent). Thus, researchers and coaches should be careful in the prescription and control of training intensity, since different combinations of swim technique may occur between the continuous and intermittent exercise.

**Acknowledgments**

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**References**


**Relationship between the oxygen uptake efficiency plateau and the individual anaerobic threshold in endurance swimmers**

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**Keywords:** oxygen uptake efficiency, velocity at individual anaerobic threshold, swimming

**Abstract**

**Introduction.** The oxygen uptake efficiency slope (OUES) has been proposed as a valid index for the objective estimation of cardiopulmonary function during submaximal laboratory testing (Baba et al. 1996). OUES is strongly correlated with maximal oxygen uptake (VO₂max) and has been observed to reach its highest and leveling off values (plateau—OUEP) near the anaerobic threshold (AT) in patients with cardiorespiratory disease and normal subjects (Sun, Hansen & Stringer 2012). However, OUES and OUEP have never been studied in highly trained athletes, particularly swimmers. The purpose of this study was to compare the velocity and oxygen uptake efficiency (OUE) values obtained during OUEP and individual anaerobic threshold (IAnT) in well trained swimmers.

**Methods.** Eight female endurance swimmers (17.5 ± 1.9 yrs, 1.71 ± 0.06 m, 62.1 ± 6.2 kg) performed an intermittent incremental swimming step test (7 x 200 m, with increments of 0.05 m·s⁻¹ and 30 s intervals). OUES was calculated by the ratio of oxygen uptake and minute ventilation. The IAnT was
determined by the velocity vs. lactate curve modeling method. ANOVA for repeated measures and regression analysis were performed to test differences between methods (p<0.05).

**Results.** Similar velocity (1.20 ± 0.05 vs. 1.22 ± 0.05 m.s\(^{-1}\)) and OUE values (43.9 ± 5.83 vs. 42.9 ± 5.8 mLO₂.L\(^{-1}\)VE\(^{-1}\)) were obtained during OUEP and IAnT calculated intensities, respectively. Regarding the Passing & Bablok regression analysis and the Pearson’s coefficient of determination, velocity (Intercept A= -0.096, Slope B= 1.071, R\(^2\)= 0.638, p<0.017) and OUE values (Intercept A= -5.360, Slope B= 1.154, R\(^2\)= 0.875, p<0.001) obtained both at the OUEP and at the IAnT were highly correlated.

**Conclusion.** These findings suggest that OUEP has a practical application in swimming as a non-invasive submaximal index closely related to the IAnT in well-trained female endurance swimmers.

**Acknowledgments.** This research was supported by grants from the Capes Foundation, Ministry of Education of Brazil (BEX: 0536/10-5), and Project PTDC/DES/101224/2008 (FCOMP-01-0124-FEDER-009577).

**Introduction**

Several methods have been used to assess aerobic endurance, while the measurement of maximal oxygen uptake (VO\(_{2}\)max) is the most objective and widely used. Besides VO\(_{2}\)max, other parameters, such as the anaerobic threshold (AT) and swimming economy are recognised to be important in the prediction of performance, especially in long-distance events (Bosquet, Leger & Legros 2002).

The oxygen uptake efficiency slope (OUES), expressing the ratio between oxygen uptake to minute ventilation, is considered to be a valid sub-maximal index for the measurement of cardiorespiratory fitness during laboratory testing (Baba, et al. 1996). The assessment of this index requires no maximal exercise and is significantly correlated with relevant exercise parameters, such as the peak and maximal oxygen uptake and the ventilatory threshold (Akkerman et al. 2010). Furthermore, OUES seems to be influenced by anthropometric variables, but not by the duration of the testing procedure (Baba, et al. 1996). Studies conducted with health subjects and patients with cardiorespiratory disease showed that OUE values reach a plateau (OUEP) near the anaerobic threshold. Interestingly, OUEP is considered to be more reproducible and less variable compared to OUES (Sun et al. 2012).

Meanwhile, the AT detected through blood lactate concentration values (IAnT) is presented as one of the most valid and reliable testing procedures in swimming to monitor training adaptations, evaluate the aerobic profile and prescribe training intensity (Morais et al. 2006; Pyne, Lee & Swanwick 2001). Complementary, the velocity corresponding to the IAnT is more strongly correlated with distance performance than VO\(_{2}\)max (Bassett & Howley 2000).

To date, no study has attempted to examine the relationship between OUEP and IAnT during field conditions in well trained swimmers. Thereby, the purpose of this study was to compare the swimming velocities and OUE values obtained during the OUEP and IAnT intensities in well trained swimmers.

**Methods**

Eight female endurance swimmers (age 17.5 ± 1.9 yrs, height 1.71 ± 0.06 m, body mass 62.1 ± 6.2 kg and percentage of body fat 16.4 ± 2.6%) volunteered to participate in the study, giving their written informed consent before participation. In addition, swimmers below the age of 18 yrs provided written parental consent. The participants had at least seven years of experience as competitive swimmers and their best 400 m front-crawl performance corresponded to 87.4 ± 3.5% of the 2013 25 m pool world record.

The testing sessions were performed in a 25 m indoor swimming pool, after a standard warm-up of 1000 m at moderate self-paced swim and under the same pool conditions (27-28°C). Swimmers were instructed to refrain from intense training sessions at least 24 h before testing.
Swimmers performed an intermittent and incremental front-crawl protocol, with increments of 0.05 m s\(^{-1}\) and 30 s rest intervals between each 200 m steps to assess IAnT and detect the swimming velocities associated with the OUEP. The predetermined velocity of the last step was calculated considering the best performance of the 400 m front-crawl race minus seven increments of velocity (Cardoso et al. 2003; R. J. Fernandes et al. 2006). Swimmers were advised to use in-water starts and open turns, without underwater gliding.

The swimming velocity (SV) was set and controlled using a visual underwater pacer with flashing lights on the bottom of the pool (GBK-Pacer, GBK Eletronics, Aveiro, Portugal) (Fernandes, Sousa, Machado & Vilas-Boas 2011); the lights were located 2.5 m apart along the bottom of the 25 m pool.

The VO\(_2\) and VE were measured by a telemetric portable gas analyzer (K4 b\(^2\), Cosmed, Italy), connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system (New AquaTrainer\(^R\), Cosmed, Italy), previously validated (Baldari et al. 2013). The equipment was calibrated before each test for VE with a 3 L calibrated syringe and the O\(_2\) and CO\(_2\) analyzers with standard calibration gases. The values of gas exchange were measured breath-by-breath during the test and averaged every 5 s. Heart rate (HR) was recorded continuously (Polar Electro, Kempele, Finland) throughout the test.

Collection of blood samples (BLa) were performed in the first 30 s after each step, at the earlobe using a portable lactate analyzer (Lactate Pro, Akray, Japan). The IAnT was determined by the velocity vs. lactate curve modeling method. The lactate increase inflexion point was considered to be the interception point between linear and exponential regressions to determine the exact velocity where BLa increased exponentially (Machado, Almeida, Morais, Fernandes & Vilas-Boas 2006). The OUES was calculated as the highest consecutive measurements of oxygen uptake (VO\(_2\) / minute ventilation (VE)) values briefly stabilised near the AT, before declining due to hyperventilation stimulated by the excess [H\(^+\)] and metabolic acidosis (Sun et al. 2012). In the case a swimmer did not attain the maximal velocity and/or exhaustion with the pre-defined steps, one more step was used.

Data are presented as mean (±SD). Standard statistical assumptions were checked before the analysis. ANOVA one-way for repeated measures and Passing & Bablok regression analysis (MedCalc Statistical Software, Belgium) were conducted to compare SV and OUE values obtained during OUEP and IAnT calculated intensities, complemented with Bonferroni correction and post-hoc test. The Pearson’s determination coefficient (R\(^2\)) was used. Statistical significance level was set at p ≤ 0.05.

**Results**

Table 1 presents the mean (SD) SV and OUE values obtained at the OUEP and IAnT intensities.

<table>
<thead>
<tr>
<th></th>
<th>Mean (SD) values for SV and OUE values obtained during the OUEP and IAnT intensities (n=8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SV (m.s(^{-1}))</td>
</tr>
<tr>
<td>OUEP</td>
<td>1.20 (0.05)</td>
</tr>
<tr>
<td>IAnT</td>
<td>1.22 (0.05)</td>
</tr>
</tbody>
</table>

According to Table 1, similar velocity (F\(_{1,7}\) = 2.635, p < 0.149, \(\eta\(^2\) = 0.273) and OUE values (F\(_{1,7}\) = 1.913, p < 0.209, \(\eta\(^2\) = 0.215) were observed both for OUEP and IAnT calculated intensities. Table 2 presents the mean (SD) sub-maximal BLa, HR and VO\(_2\) values corresponding to the IAnT.

<table>
<thead>
<tr>
<th></th>
<th>Mean (SD) values for the sub-maximal physiological variables corresponding to the IAnT (n=8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLa (mmol.L(^{-1}))</td>
<td>HR (b.min(^{-1}))</td>
</tr>
<tr>
<td>1.50 (0.47)</td>
<td>171.76 (5.62)</td>
</tr>
</tbody>
</table>

Table 2
The Passing & Bablok analysis and the Pearson’s determination coefficient showed that swimming velocity and OUE mean values obtained through the OUEP and IAnT intensities were highly correlated \((p \leq 0.05)\) (Table 3). Figure 1 and 2 present the Passing-Babok regression analysis and Bland-Altman plot, respectively, determined between OUES and IAnT intensities concerning the SV (Left Panel) and OUE (Right Panel) values.

In Table 3, the coefficient of determination \((R^2)\), \(p\) value and regression equation variables for the comparison between the OUEP and IAnT intensities for SV and OUE values are presented.

**Table 3**  Comparison between the OUEP and IAnT intensities for SV and OUE values

<table>
<thead>
<tr>
<th>Parameters</th>
<th>OUEP vs. IAnT</th>
<th>(R^2)</th>
<th>(p) value</th>
<th>Slope B</th>
<th>Intercept A</th>
</tr>
</thead>
<tbody>
<tr>
<td>(SV) ((m \cdot s^{-1}))</td>
<td>0.638*</td>
<td>0.017</td>
<td>1.071 ((0.339 \text{ to } 2.128))</td>
<td>-0.096 ((-1.404 \text{ to } 0.786))</td>
<td></td>
</tr>
<tr>
<td>(OUE) ((\text{mL } \text{O}_2 \cdot \text{L } \text{V}_E^{-1}))</td>
<td>0.875*</td>
<td>0.001</td>
<td>1.155 ((0.673 \text{ to } 2.351))</td>
<td>-5.360 ((-56.188 \text{ to } 14.909))</td>
<td></td>
</tr>
</tbody>
</table>

\(*p < 0.05.\)

**Figure 1**  Passing-Babok regression analysis obtained during OUES and IAnT intensities regarding the SV (left panel) and the OUE values (right panel) \((n=8)\)

**Figure 2**  Bland-Altman plot of the OUES and IAnT intensities regarding the SV (left panel) and the OUE values (right panel) \((n=8)\)

**Discussion**

The current study presents sub-maximal OUE values obtained in well-trained female endurance swimmers, as well as comparison between OUEP and IAnT intensities regarding both OUE and SV. The
main findings indicate that SV as well as OUE values attained during OUEP and IAnT intensities are highly correlated and not significantly different, suggesting that they both refer to the same biophysical state of the swimmer.

Caution must be taken when comparing SV, BLa and HR mean values corresponding to the IAnT of our participants with those from other studies, due to the inconsistency regarding the methodology applied for the IAnT determination in swimming. Approaches usually include SV and HR values at: (i) the fixed 4 mmol·L⁻¹ BLa, (ii) at the final step of the incremental test, (iii) during different testing procedures (i.e., 2 to 7 x 200 m step tests) or, (iv) include the mathematical approach to determine the individual IAnT (Altimari, Altimari, Gulak & Chacon-Mikahil 2007; Anderson, Hopkins, Roberts & Pyne 2006; Fernandes et al. 2010; Pyne, Anderson & Hopkins 2006). Nevertheless, Pyne et al. (2001) and Thanopoulos (2010) presented higher BLa values at the IAnT than those reported in this study (3.6 and 5.5 mmol·L⁻¹ in world-ranked male/female and national level female swimmers, respectively). Similarly, in the latter study the SV values corresponding to the IAnT were higher than those presented here (1.45 vs. 1.22 m·s⁻¹). At least partially, differences might be attributed to the performance level of the swimmers.

Sub-maximal OUE values presented in this study are in accordance with those reported by Akkerman, et al. (2010), despite the differences in the conditions used for exercise testing (cycle ergometer vs. free swimming) and the chronological age of the participants (12.9 ± 2.6 vs. 17.5 ± 1.9 yrs). Sun et al. (2012) showed that OUES is significantly influenced by age and body size.

To our knowledge, this is the first attempt to examine the practical application of the OUEP method by correlating and comparing OUE and SV values obtained during OUEP and a widely accepted field test, such as the IAnT, in well-trained swimmers. From a practical point of view, OUEP may be used to assess IAnT without using intrusive procedures. Furthermore, once OUES indicates ventilatory efficiency with regard to VO₂ (Akkerman, et al. 2010), the leveling off values of OUES at the intensity correspondent to the IAnT, implies that, at this particular intensity, a deleterious effect of exercise intensity is observed over the respiratory dynamics. OUES may be also used as a potential sub-maximal index of swimming economy, since the latter is considered to be an efficiency index, expressing the VO₂ required to maintain a given swimming velocity. Since distance swimming performance is significantly influenced by the VO₂max and the AT, the results obtained during this study can provide valuable information for designing training programs in swimmers. Future work should focus on examining the efficacy of the OUES and OUEP indeces in determining adaptations after a training period.

Acknowledgments

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References


Stroke mechanics profile and swimming economy during progressive VO2max test

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Keywords: crawl stroke, energy cost, aerobic assessment

Abstract

Introduction: The relationship of distance per stroke (Ds) and stroke rate (SR) with velocity (v) progression, over a range of swimming intensities within aerobic energy supply, did not evidence how Ds and SR slopes (Ds_slope and SR_slope, as well as, the crossing point (Cp) between them) change their profiles during maximal aerobic test, and what is the parameter of endurance capacity (among gas exchange threshold (GET), respiratory compensation point (RCP), maximal oxygen uptake (VO2max), and economy (e)) that correlates better to these changes.

Purpose: The aim was to highlight the physiological responses associated to Ds and SR changes as swimming velocity increases. Even, analyze if Ds and SR are reliable indices to control training and/or improvements in aerobic pace.

Methods: Nine subjects performed a continuous incremental test (300m per stage) until volitional exhaustion. Each stage was designed by percentages of the maximal crawl velocity in 400m (%v400). VO2max, GET and RCP were examined. The velocities corresponding to VO2max (vVO2max), GET


(vGET) and RCP (vRCP) were identified. SR was determined from the time taking to complete three strokes. Ds was calculated from equation \( v = D_s \times SR \). The slopes were determined in \( x = -b/2a \) and \( y = -(D/4a) \), where \( D = b^2 - 4ac \) given \( Ds_{slope} \) and \( SR_{slope} \). The \( v \) and \( VO_2 \) at \( Cp \) (vCp and \( VO_2(Cp) \)) were determined from the intersection point of the adjusted algorithms. \( VO_2 \) and \( v \) were adjusted from a power function \( f(y) = x^n \). Economy was quantified at \( Ds_{slope} \) and \( SR_{slope} \) by means of \( VO_2 \) and the caloric coefficient for \( VO_2 \) (20.1kJ).

**Results:** Taking values of \( VO_2(max) = 4458 \pm 645 \text{ ml\times min}^{-1} \) as reference of maximal aerobic rate pace, GET and RCP were locating at 63 and 77% of \( VO_2(max) \). \( VO_2(Ds_{slope}) \) and \( VO_2(SR_{slope}) \) were observed to be located at 122%, 68% and 49% of \( VO_2(max) \), respectively. These results mean that swimming intensity paced by \( VO_2(Cp) \) would require great anaerobic demand, since it was located above aerobic maximal rate pace, and that \( Ds_{slope} \) and \( SR_{slope} \) are reliable indexes of aerobic pace, but they could not be used interchangeably. \( Ds_{slope} \) seems to be appropriated to develop endurance capacity, since it located swimming intensity in heavy domain of exercise, while \( SR_{slope} \) parameterises the moderate domains of exercise, which is better applied between high intensity sections of training or to pace active rest. The economy from expected \( VO_2 \) at \( Ds_{slope} \) \( (0.84 \pm 0.18 \text{ kJ\times m}^{-1}) \) and \( SR_{slope} \) \( (0.68 \pm 0.16 \text{ kJ\times m}^{-1}) \) evidenced correlations with GET \( (r = 0.76\) and \( 0.70, \) respectively), but at \( vCp \) \( (1.13 \pm 0.19 \text{ kJ\times m}^{-1}) \) none correlations were observed.

**Conclusions:** Thus, Ds and SR showed an independent turn point profile for \( VO_2 \) response, as swimming velocity increases. Moreover, Ds and SR influenced better the swimming velocity at GET than at RCP, showing that GET is the metabolic reference beyond which stroke profile could not ensure an economic pace.

**Introduction**

Distance per stroke (Ds) and stroke rate (SR) changes as swimming velocity (v) progress over a range of aerobic swim intensities, and the profile of changes of these mechanical parameters of swimming stroke have been correlates to aerobic pace indexes, as physiological thresholds of aerobic scope (Wakayoshi et al. 1993). Thus, Ds and SR are able to prescribe aerobic training and monitoring improvements of endurance capacity, i.e. mechanical changes in the relationship of Ds and SR with swimming velocity occurs up to the limit of 60%VO2peak or up to anaerobic threshold (Wakayoshi et al. 1995). Additionally, the peak of Ds response to swimming velocity increments had a tendency to occur between 65-70% of the 200-m maximal swimming performance, and be better related to Lactate Threshold (LT) than the onset of blood lactate appearance (vOBLA) (Nomura & Shimoyama 2003). In this sense, Ds and SR profile analysis would give important insights about exercise physiological domain, helping training control, as well as, evaluating technical ability improvements by means of mechanical proficiency at submaximal velocities (economy) (Graig et al. 1985, Kersken and Komi 1988; Toussaint 1992; Pendergast et al. 2006).

However, most of these relationships had been established from oxygen uptake (VO2) sampling intermittently after swimming trials of the test. The effectiveness of \( VO_2 \) measurements from breath-by-breath technique coupled to a specific respiratory valve and snorkel would give further information about the relationship between \( VO_2 \), swimming velocity, SR and Ds. Take during maximal aerobic test, further evidence on correlation of Ds and SR to the determinants of endurance performance (gas exchange threshold (GET), respiratory compensation point (RCP), maximal \( VO_2 \) (\( VO_2(max) \), and economy (e)), should determine the potential for swimming success, guide training schedule and race strategy.

**Objective**

This study aimed to verify how the profile of Ds and SR would be associated to \( VO_2 \) responses during maximal progressive aerobic test in crawl swimming. Even, by locating the slopes of Ds (\( Ds_{slope} \)) and SR (\( SR_{slope} \)), as well as, the crossing point (Cp) between profiles into exercise domains, we analyzed the
suitability of these strokes indexes to control aerobic pace, what was further ensured by verifying the correlation level of swimming economy in $D_{slope}$, $SR_{slope}$ and $Cp$ to the swimming velocity at GET, RCP, $VO_2$.

**Methods**

Nine well-trained endurance swimmers (68.6± 9.1 kg body weight, 178.2± 6.4 cm height, 21.0± 7.1 years old and 13.1± 4.0% body fat mass) performed continuously a five to eight stages progressive aerobic test (300-m per stage, with 30 seconds of rest between each stage) until volitional exhaustion (unable to keep required rate pace unchanged during 300m or/and stop before stage end) to evaluate $VO_2_{max}$, GET and RCP. The participants were instructed to avoid intense training sessions, as well as, beverage containing caffeine or alcohol at least 24h before the experimental sessions. All subjects were informed about experimental conditions and given their consent to the participation. This investigation was approved by local Ethical Committee.

Progressive aerobic test was designed with incremental steps based on the maximal crawl velocity in 400-m (%v400-m). Initial intensity was set at 70% of v400-m, and increased by 5% at each step. The velocity control during each stage was pacing by lap time for every 50 meters. An experienced professional performed the control of the stopwatch and feedback the swimmer from pool side.$VO_2_{max}$ was calculated as the highest average (9s) value reached during the incremental test, after 3s filtered breath-by-breath $VO_2$ curve. Attainment of $VO_2_{max}$ during the test was confirmed by the occurrence of at least two of the following criteria: plateau phenomenon in $VO_2$ (variation less than 150 mL.min$^{-1}$) despite increases in exercise intensity, a respiratory exchange ratio (RER) above 1.10, and heart rate above 95% of age-predicted maximum (220 – age) (Poole et al. 2008). During the exercise tests, pulmonary gas exchange was determined breath-by-breath with a portable automated system (K4b2, Cosmed), which was calibrated before each test, and connected to the swimmer by a special respiratory snorkel and valve system, previously validated by Kerskinen et al. (2003). All tests were performed in a 50-m indoor swimming pool, using open-turn in each lap.

GET and RCP were examined visually by two independent investigators, using the responses from the $V_i/VO_2$, $V_i/VO_2$, $PETCO_2$ and $PETO_2$ parameters. According to Beaver et al. (1986), GET criteria is the first increase in the $V_i/VO_2$ and in $PETCO_2$, without a comitant change in $V_i/VO_2$ and $PETCO_2$, respectively; whereas RCP is observed just before the continuous increase in $V_i/VO_2$ and $V_i/VO_2$ with a comitant reduction in $PETCO_2$. The $v$ at $VO_2_{max}$ ($vVO_2_{max}$), GET ($vGET$) and RCP ($vRCP$) corresponding to the stage where each parameter was identified.

SR was determined from the time lasting to complete three strokes, using Seiko stopwatch and taking from pool side for every 50 meters (between 20 to 30 meters, preferentially). $D_s$ was calculated from equation $v = D_s \times SR$. Concern the way that SR and $D_s$ were assessed, it considered the feasibility (low cost, no need for technical support, and time saving) taking into account all professional daily tasks on pool side. Similar procedure was successfully applied to Wakayoshi et al. (1995). A second order polynomial function was applied to adjust $D_s$ and SR (y) to $v$ and $VO_2$ (x) for each subject’s progressive test. The slope were determined in x ($-b/2a$) and y ($-D/4a$, where $D = b^2 - 4ac$), given $v$ and $VO_2$ at each slope ($vD_{slope}$, $vSR_{slope}$, $VO_2DS_{slope}$ and $VO_2SR_{slope}$). The $v$ and $VO_2$ at $Cp$ ($vCp$ and $VO_2Cp$) were determined from the intersection point, after equaling to zero and solving to x the algorithms for $D_s$ and SR adjustments to $v$ and $VO_2$. $VO_2$ ($y$) and $v$ ($x$) was adjusted from a power function ($f(y) = x^b$). Economy was quantified at $vD_{slope}$, $vSR_{slope}$, and $vCp$ by means of the individual power relationship between $VO_2$ and $v$ and the arbitrary caloric coefficient for $VO_2$ (20.1kJ).

Data set was first tested for normality by Shapiro-Wilk test. The mean values of $v$ and $VO_2$ corresponding to GET and RCP were contrasted to the values of $v$ and $VO_2$ corresponding to $D_{slope}$, $SR_{slope}$, and $Cp$ by ANOVA test (one-way, with LSD as post-hoc analyze). Economy at $vD_{slope}$, $vSR_{slope}$, and $vCp$ was correlated to $vVO_2_{max}$, $vGET$ and $vRCP$ by Pearson’s coefficient, using SPSS 18 statistical package and significant level set at $p \leq 0.05$. 
Results

VO₂ and stroke parameters adjustments to the progression of crawl swimming velocity during aerobic test are shown in Figure 1. The second-order polynomial relationships between Ds and SR with v gave the higher coefficient of adjustment for each swimmer performance on aerobic test. Group adjustment reflects a trend of Ds to decreases after 1.2 ± 0.2 m×s⁻¹, and SR increases after 1.06 ± 0.14 m×s⁻¹, matching each other (Cp) at 1.59 ± 0.11 m×s⁻¹. When related to the mean VO₂ response to v increments, Ds trend to decrease after 3072 ± 1091 ml×min⁻¹, SR increase after 2162 ± 669 ml×min⁻¹, and project VO₂ at Cp was 5375 ± 966 ml×min⁻¹. The peak of Ds, after which it trend to decrease (2.5 ± 0.3 m×str⁻¹), occurred at a higher swimming velocity than that where SR begins to increase (0.46 ± 0.14 str×s⁻¹) (Figure 2).

SR = 1.0529v² - 1.9766v
+ 1.3354 - R² = 0.998

SR (strokes x s⁻¹)

SL = -3.4816v² + 7.6155v
- 1.6049 - R² = 0.993

SL (m x stroke⁻¹)

VO₂ = 1562.1v³⁻¹.₅
R² = 0.997

VO₂ (ml x min⁻¹)

velocity (m x s⁻¹)

Figure 1 SR, SL and VO₂ profiles across swimming velocity progression. Best slope adjustments were drawn by mean group values

From the reference of VO₂max (4458 ± 645 ml×min⁻¹) and vVO₂max (1.40 ± 0.03 m×s⁻¹), the GET and RCP were located at 63.0 ± 9.5 and 77.2 ± 11.0% of VO₂max, and at 86.4 ± 3.7 and 93.8 ±2.3% of vVO₂max, respectively (Figure 2). The observed vCp (113.6 ± 8.7% of vVO₂max), VO₂Cp (121.6 ± 22.0% of VO₂max), vDs_slope (85.7 ± 12.7% VO₂max), VO₂Ds_slope (68.3 ± 18.4% of VO₂max), vSR_slope (75.5 ± 10.4% of vVO₂max), and VO₂SR_slope (48.5 ± 11.7% of VO₂max) associated vDs_slope, vSR_slope, and vCp to severe, heavy and moderate domains of exercise, respectively. Swimming economy calculated at vDs_slope (0.84 ± 0.18kJ×m⁻¹) and vSR_slope (0.68 ± 0.16kJ×m⁻¹) evidenced correlations to velocity at GET (r = 0.76 and 0.70, respectively), while the correlations to RCP (r = 0.47 and 0.43, respectively) had no significance. At vCp, the swimming economy (1.13 ± 0.19kJ×m⁻¹) did not correlated significantly to velocity at GET (r = 0.56) and RCP (r = 0.43). None of strokes parameter exhibited correlations to vVO₂max.
Figure 2  SR and SL vs. VO\textsubscript{2} profile across progressive test performance. See text for further details

Table 1 shows the percentage where GET, RCP, Cp, D\textsubscript{slope} and SR\textsubscript{slope} were located relative to maximal aerobic velocity and VO\textsubscript{2max}. The percentage where SR trend to increase (SR\textsubscript{slope}) is located differs from the percentage where GET, RCP, Cp and D\textsubscript{slope} are located relative to maximal aerobic velocity and VO\textsubscript{2max}. No differences were observed to Ds trend to decrease (Ds\textsubscript{slope}) with %vVO\textsubscript{2max} and %VO\textsubscript{2} at GET, and %VO\textsubscript{2} at RCP, but Ds\textsubscript{slope} differed from %vVO\textsubscript{2max} and %VO\textsubscript{2} at Cp. The results above show Cp localisation at %vVO\textsubscript{2max} and %VO\textsubscript{2max} differed from all other physiological (GET and RCP) and stroke (SR\textsubscript{slope}, Ds\textsubscript{slope}) references in maximal progressive aerobic test.

Table 1  Aerobic parameters and swimming stroke reference during maximal test

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO\textsubscript{2max} (ml\cdot kg\cdot 1\cdot min\cdot 1)</td>
<td>65,4</td>
<td>8,6</td>
</tr>
<tr>
<td>vVO\textsubscript{2max} (m\cdot s\cdot 1)</td>
<td>1,40</td>
<td>0,03</td>
</tr>
<tr>
<td>GET (%VO\textsubscript{2max})</td>
<td>63,0\textsuperscript{a}</td>
<td>9,5</td>
</tr>
<tr>
<td>vGET (%vVO\textsubscript{2max})</td>
<td>86,4\textsuperscript{c}</td>
<td>3,7</td>
</tr>
<tr>
<td>RCP (%VO\textsubscript{2max})</td>
<td>77,2\textsuperscript{a}</td>
<td>11,0</td>
</tr>
<tr>
<td>vRCP (%vVO\textsubscript{2max})</td>
<td>93,8\textsuperscript{c}</td>
<td>2,3</td>
</tr>
<tr>
<td>Cp (%VO\textsubscript{2max})*</td>
<td>121,6\textsuperscript{a}</td>
<td>21,98</td>
</tr>
<tr>
<td>vCp (%vVO\textsubscript{2max})\textsuperscript{•}</td>
<td>113,5\textsuperscript{b}</td>
<td>8,69</td>
</tr>
<tr>
<td>D\textsubscript{slope} (%VO\textsubscript{2max})*</td>
<td>68,31\textsuperscript{†}</td>
<td>18,37</td>
</tr>
<tr>
<td>vD\textsubscript{slope} (%vVO\textsubscript{2max})\textsuperscript{†}</td>
<td>85,86\textsuperscript{*}</td>
<td>12,71</td>
</tr>
<tr>
<td>SR\textsubscript{slope} (%VO\textsubscript{2max})\textsuperscript{‡}</td>
<td>48,52\textsuperscript{†}</td>
<td>11,74</td>
</tr>
<tr>
<td>vSR\textsubscript{slope} (%vVO\textsubscript{2max})\textsuperscript{‡}</td>
<td>75,53\textsuperscript{*}</td>
<td>10,37</td>
</tr>
</tbody>
</table>

\textsuperscript{a/b/c/d/e} Differences with significance at 0.05.

Discussion

The main find of this investigation was that the point where Ds begin to decrease and SR increase is each other independent from both metabolic (VO\textsubscript{2}) and mechanical (v) point of view. In turn, Cp failed to demonstrate any influence on aerobic parameters. The observed second-order polynomial relationships between Ds and SR to swimming velocity, and the cubic relationship between swimming velocity and VO\textsubscript{2}, are in line to the work of Wakayoshi et al. (1995).
The values for $D_{slope}$ ($2.46 \pm 0.42 \text{ m} \times \text{s}^{-1}$) and $S_{slope}$ ($0.48 \pm 0.09 \text{ s} \times \text{s}^{-1}$) among competitive swimmers, at a standard power output reference of 1000 W ($\pm 2.86 \text{ lO}_2 \times \text{min}^{-1}$) (Toussaint 1992) are closest to our results, confirming the swimmer high level in the present study. $S_{slope}$ exhibited a tendency to increase early during progressive test (i.e. bellow GET), and $D_{slope}$ could be keep unchanged at high values even above GET. However, the crossing point (Cp) between $S$ and $D$ profiles had no evidence over aerobic velocity range in the present research. Physiological significance of $D_{slope}$ was supported by other researches to the relationship with velocity at onset of blood lactate accumulation (OBLA) (Wakayoshi et al. 1995), lactate threshold (LT) (Nomura; Shimoyama 2003), and maximal lactate steady state (MLSS) (Dekerle et al. 2005). Thus, $D_{slope}$ would indicate a biomechanical turning point, as swimming velocity progress above $D_{slope}$, which is consistent with an increment in anaerobic demand and $S$ increase (Wakayoshi et al. 1995). From the analysis of physiological areas for training pace (Troup 1986), $D_{slope}$ suggest to demarcate a swimming intensity for aerobic overload. Despite our results supported the correlation of velocity economy at $D$ and $S$ with velocity at GET, only $D$ did not differ from velocity and $V_{O2}$ at GET, corroborating the reliability of $D_{slope}$ to reflect physiological response to exercise in heavy domain. Therefore, $D_{slope}$ and $S_{slope}$ had similarities in the profile of response to velocity increments, but markedly different slopes, which is better related to the assumption that skilled swimmer are able to increase $S$ without (or, at least, less) concomitant $D$s decrements than counterparts with poor technical proficiency (Graig et al. 1985; Kerskinen & Komi 1988; Toussaint 1992). $S_{slope}$ should be better applied to pace moderate exercise intensity, which is appropriated to enhance endurance capacity during early phases of training period, or keep endurance levels unchanged during training phases with high intensity and low volume strategies. On the other hand, Cp would be best applied to represent lactate tolerance pace: an exercise stimulus able to elicit $V_{O2}$max and continuously blood lactate rising until exercise end.

Concern swimming economy, it was hypothesised that maximal swimming velocity is directed related to energy input and inversely related to economy ($V_{\text{max}} = E_{\text{Total}} \times \text{Economy}^{-1}$), additionally a better mechanical efficiency improves economy and increase $D$s during swimming at a given submaximal velocity (Pendergast et al. 2006; Pendergast et al. 2003; Capelli et al. 1998). The results from the present study showed swimming cost increases continuously throughout aerobic progressive test, changing from mean values of 0.73 ($\pm 0.13 \text{ kJ} \times \text{m}^{-1}$) to 1.06 ($\pm 0.16 \text{ kJ} \times \text{m}^{-1}$). However, swimming economy observed at velocities corresponding to stroke parameters ($D_{slope}$, $S_{slope}$ and Cp) had no correlation to $V_{O2}$max, which means that proficiency indexes of stroke mechanics have better influence on submaximal aerobic velocities. However, swimming cost at $vV_{O2}$max ($1.06 \pm 0.16 \text{kJ} \times \text{m}^{-1}$) was positively and highly correlated ($r = 0.99$) to $V_{O2}$max, corroborating the inversely relationship between economy and $V_{O2}$max observed in other sport modalities (Billat & Koralsztein 1996).

**Conclusions**

$D_{slope}$ and $S_{slope}$ showed an independent turn point profile, as analyzed from $V_{O2}$ response for velocity increments. Moreover, $D_{slope}$ and $S_{slope}$ have a tendency to influence better the intensity at GET than RCP, which probably refers both to the range of exercise intensity dictated aerobic overload (applied to develop endurance capacity) and aerobic pace (applied to maintenance of endurance capacity, or provide recuperation from series with maximal swimming intensities), respectively. In turn, Cp failed to demonstrate influence on aerobic parameters, but able to characterises lactate tolerance pace.

**Acknowledgments**

We are grateful to the RENOVE (PROPe-UNESP) and CNPq (479262/2013-6) for financial support.

**References**


Diagnostics of specific working capability and evaluation of adaptation to training workloads during sport season in open water swimmers

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Keywords: open water, swimming, step test, specific working capability, lactate curve, aerobic and anaerobic threshold

Introduction

Regular evaluation of functional diagnostics tests is needed in order to increase the efficiency of active control in the process of monitoring of functional state of the swimmer, and the tests must be conducted in circumstances specific for the precise type of sport. At the same time the specifics of muscular activity and the orientation of the training process are defining the features of the diagnostics of functional state of the swimmers, which is, in turn, oriented to control the adaptation processes of those systems and functions of the swimmer’s body that are principal for swimming in open water. The bio-energetic potential is a key factor for achieving high results for swimmers who compete on long and very long distances.
E. Maglischo’s ‘Swimming fastest’ is going through the issue of evaluation the aerobic and anaerobic capacities of swimmers in detail. Around 10 methods are given to individually estimate the aerobic and anaerobic threshold using the invasive procedure of measuring the blood lactate and it is pointed out that each of them we can use for the gathered data correlates well with aerobic efficiency of swimmers [1]. Nevertheless, the static values of lactate are also used in training practice as they allow to trace the dynamics of the bio-energetic potential of the swimmer via standard protocol which allows us to evaluate the quality of work objectively over the year.

The aim of this study was to design a method for diagnostics of specific working capability of swimmers in open water with a specific competitive activities

**Methods**

The evaluation of the special preparedness was conducted by means of a swimming step test in form of 10 x 400 m with 1 minute of rest in the swimming pool. The swimmer performs the test alone.

400 meters segments used in the tests were chosen in correspondence with the average interval between the turning buoys on the distances of 5, 10 and 25 kilometers used in World Championship 2013 in Barcelona.

We should also mention that the conducted analysis of the competitive activity on the international races in open water shows that the tactical features of passing the distance imply the increasing speed over the course of race.

The individual values of swimming speed for each segment is set during the test.

The initial speed is assigned on the basis of 80% of the personal best of the swimmer, with graded enhancement of speed on 400 m with each next segment, reaching the maximum speed on the last one. The test design is as follows: first load step – 3 x 400 m, second – 2x400 m, third – 2x400 m, fourth – 2x400 m, and the last one— 400 m maximum.

The following parameters were analyzed after each step's segment: time of the segment, stroke rate, stroke length, heart rate (via POLAR telemetric monitor).

The blood lactate concentration was measured using the Lactate Scout lactometer after each load step at the second minutes of rest.

In the longitudinal study we've treated a total of 90 tests among women and 88 among men, all the subjects are national and international level sportsmen specialised in long-distance swimming.

**Results and discussion**

The suggested test corresponds with the features of swimmers’ competitive activities and at the same time permits achieving the stable status of functional systems during the workload step.

Analyzing the correlation between the swimming speed and the lactate concentration in the tests we’ve built a lactate curve, which was approximated to exponential curve (fig.1).

Dividing the derived curve is sections we’ve found the swimming speed zone’s borders, which were different in nature of the energy supply [2].
Tables 1 and 2 provide us with the generalised values for lactate level in the blood of swimmers doing the graded 10x400 meters test. (90 tests for women and 88 for men specialised on long distances).

**Table 1**  
**Blood lactate concentration at first step in the test 10x400 m with increases velocity**

<table>
<thead>
<tr>
<th></th>
<th>Mean (mmol/L)</th>
<th>SD (mmol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>1,9</td>
<td>0,5</td>
</tr>
<tr>
<td>Females</td>
<td>1,9</td>
<td>0,6</td>
</tr>
</tbody>
</table>

**Table 2**  
**Blood lactate concentration at the end of the 10 pieces in the test 10x400 m with increases velocity**

<table>
<thead>
<tr>
<th></th>
<th>Maximum (mmol/L)</th>
<th>Mean (mmol/L)</th>
<th>SD (mmol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>17,1</td>
<td>9,7</td>
<td>2,5</td>
</tr>
<tr>
<td>Females</td>
<td>13,6</td>
<td>7,4</td>
<td>1,9</td>
</tr>
</tbody>
</table>

Data range gathered using the 10x400 m test and represented by tables 1 and 2 shows us that aerobic and anaerobic threshold can be determined as lying within the borders of the individual data corpus of the swimmers.

The re-calculation of energetic zones velocity data combined with re-calculation of swimming pool test velocity excluding turns permits us to compare to gathered data with the average lap velocity during an open water race.

The dynamic observations and the analysis of the variation in different links of the lactate curves are of the most practical benefit. They are the effect of executing training programs of various duration and orientation. Figure 2 represents the dynamics of the lactate curves during the training cycle for swimming in open water.
Figure 2 Example of the change of lactate curves in a year training cycle by using test 10x400 m with increases velocity

The attribute of the annual cycle of training is increasing speed of swimming in the zone from aerobic threshold (blood lactate 2 mmol/L) to VO2max (blood lactate 8 mmol/L).

Localisation of aerobic and anaerobic threshold for different swimmers is individual. It is ridden by biological nature (the muscular fibers of different kind ratio, ferment system activity etc.), as well as the distance specialisation and the nature of training process aiming at developing certain physical qualities.

The cumulative parameters of the swimming techniques (stroke rate and stroke length) in the different zones of energy-supply, acquired as a result of a testing, allow the coach to evaluate the change of the swimmer’s movement structure as an effect of fatigue and compare them to the corresponding figures of the competitive activity.

**Conclusions**

Systematic studying of the dynamics of lactate curves in training allows us to analyze and adjust workload based on it’s size and it’s primary impact on certain systems of the organism.

Thus, the presented testing technology for open water swimmers allows: 1) evaluate the level of preparedness of the swimmer in the energy-supply zones specific for this type of sport, 2) execute the proper comparison of these figures all over the training year, 3) make alterations to the intensity of training workloads and training velocity, 4) carry out the comparative evaluation of the swimmer’s potential realisation efficiency on the competitions.

**References**

**Validation of an inertial measurement unit for the determination of the longitudinal speed of a swimmer**

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**Keywords:** validation, IMU, inertial sensors, speed, swimming

**Introduction**

In swimming, the athlete’s performance is reflected by swimming speed. Unfortunately, this measurement remains difficult due to the specific constraints of testing in an aquatic environment. Either the method constrains the task that can be analysed (only one length can be swum when using speedometers; Craig, Termin & Pendergast 2006; Schnitzler et al. 2010) or the method, that offers greater flexibility, is complex, time-consuming and/or can not guarantee acquisition of all desirable data (such as bubbles around the swimmer’s body and line-of-sight difficulties in the case of video based systems; Callaway, Cobb & Jones 2009; Puel et al. 2012).

Technological advances however, that overcome these concerns are beginning to change the way we measure (and in turn perceive) athletic performance. The past twenty years has seen the increasing use of inertial measurement units in the study of human movements (Cuesta-Vargas, Galán-Mercant & Williams 2010) and sports biomechanics, including swimming (Ohgi 2002; Dadashi et al. 2011; Stamm et al. 2011), especially as these systems becoming more financially feasible (Mayagoitia, Nene, Veltink 2002).

The aim of this study was to validate an inertial measurement unit prototype specifically designed for swimmer movement analysis (CIREN, Actris, Brest, France; Figure 1), against current gold standards for estimating rotational speeds, translational accelerations and longitudinal speed of the swimmer relative to a global reference frame.

**Methods**

The CIREN prototype is based on a NANO MEMSense inertial measurement unit that consists of a combined three-axis accelerometer sensor (± 5 g), magnetometer (± 1.9 Gauss) and gyroscope (± 600 °/s) and an embedded data logger, which records at 150 Hz. The sensor is assembled within a sealed housing (IP68, outer dimensions are 117 x 80 x 33 mm).
This study involved three different experiments.

The first one was conducted in a mechanical lab where CIREN was mounted on a MIKRON HSM 600U, a 5-axis machining centre that can reproduce and control chosen trajectories (Figure 2). Different sets of movements were tested (50 repetitions of one-axis rotation or one-axis translation).

![Prototype's initial positions when mounted on the mobile plate of the machining tool](image)

The following two experiments were then conducted in a pool and involved a sample of experienced swimmers. Participants wore CIREN, placed on the lower back, secured by a belt and belt loops specifically designed in the unit to mount it firmly (Figure 3).

![Prototype's position when worn by a swimmer](image)

The longitudinal speed of the swimmer was determined by three methods: the use of CIREN v6.0 software (Figure 4), which integrates all embedded sensors and predefined initial constraints (initial position of the swimmer and pool length); a speedometer, and; via a multi-camera video system.

In Experiment 2, CIREN was compared with a tethered speedometer, used as the velocity measurement reference (Leblanc et al. 2007; Schnitzler et al. 2010; Dadashi et al. 2012). One regional swimmer swam a 25-m in her stroke speciality (breaststroke) and at her training pace.

In Experiment 3, one international swimmer swam an all-out 25 m in front crawl and comparisons were made between CIREN and 3D video based kinematics (5 aerial cameras, videos deinterlaced at 50 Hz, data extrapolated at 150 Hz to match sensor’s data, calibration frame with 49 calibration points, 3.67 x 1.63 x 1.42 m).
Statistics
For analysis of both the first and the third experiment Spearman’s correlations ($r$), normalised pairwise variability index (nPVI; Sandnes & Jian 2004) and the percentage of signal outside the confidence interval (CI) of Bland & Altman were computed. For the first experiment, no smoothing or filtering was applied to the data, whether from the inertial measurement system or from the machining centre. Therefore, the comparison concerns the raw signals on the entire lengths of the acquisitions.

For analysis of the second experiment the discrete relative phase was computed (Zanone & Kelso 1992). Two maximum and two minimum local peaks by cycle were taken into account.

Results
Experimentation 1
The rotation test showed excellent agreement: $0.82 < r < 0.84$ ($p < 0.0001$), $1.08 < nPVI < 1.21$ and the percentage of signal outside CI from 2.67 to 3.16% (3418 samples). As did the translation test: $0.18 < r < 0.28$ ($p < 0.0001$), $2.11 < nPVI < 4.25$ and the percentage of signal outside CI from 2.01 to 2.63% (3455 samples). Figures 2 and 3 present respectively rotational speeds and translational accelerations by means of the MIKRON machining tool and CIREN.
Figure 3  Translational accelerations by means of the gold standard (MIKRON machining tool, dark dashed) and the prototype (grey line).

Experimentation 2

Figure 4 presents longitudinal speeds of the hip in breaststroke for speedometer and CIREN. The analysis of 28 consecutive local peaks shows that speedometer’s signal was slightly in advance (6.7 °) and the mean discrete relative phase was 21.2 ± 16.8°.

Figure 4  Longitudinal speeds of the hip in breaststroke for the gold standard (speedometer, dark dashed) and the prototype (grey line)

Experimentation 3

Figure 5 presents longitudinal speeds of the hip in crawl for 3D kinematics and CIREN. Point by point comparison revealed $r = 0.49 \ (p < 0.0001)$, nPVI = 0.11 and the percentage of signal outside CI = 3.57%.
Discussion

When compared to well-tried mechanical system, CIREN provides rotational speeds and translational accelerations that are in excellent agreement, validating the system under the tested ranges of motion.

In swimming, the longitudinal speed computed by CIREN appears more sensitive and presents smaller amplitudes than the speedometer’s signal, presumably because of the speedometer’s design (a motor used as generator that measures the speed of wire unwinding) and also because a torque is applied to keep the cable tight, reasons that could mask some of the more subtle high speed variations related to the extra amplitudes apparent in the CIREN signal. Furthermore, speedometer’s average speed appears to be lower than CIREN’s average speed got by timing. However, the CIREN’s drift correction conceals any change in the average speed during the test, nevertheless the magnitude and pace are not affected.

The third experiment showed good agreement between the signals from CIREN and 3D kinematics. The longitudinal speed computed by CIREN can be considered as valid in the context of high-level swimmer analysis. Indeed, the speed curve clearly shows the stroke cycles and a simple check of frequencies confirm this conclusion.

Conclusions

CIREN provides a good estimation of the instantaneous speed of the swimmer and, beyond that, allows consideration of movement variability (stroke frequency).

Compared to conventional systems, additional features lie not only in the analysis of roll, but also in the continuous analysis over the entire length of the pool, even for tests for which the distance to swim is greater than one pool length. Furthermore, CIREN improves the low frequency of conventional video analysis system, facilitates the implementation of the study (no complicated set-up), limits the inconvenience caused by wearing a measure system, and finally speeds up the feedback to the operator (coach, sport scientist, etc.).

In perspective, it would be interesting to compare, in a laboratory situation, our prototype with another mechanical systems able to reproduce the 3D motion of the swimmer along with translation in order to further confirm the validity of the CIREN protocol for the evaluation of speed.
Acknowledgments

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References


Altitude training enhances performance in elite swimmers: results from a controlled four parallel groups trial (The Altitude Project)

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Keywords: hypoxia, swimming, haemoglobin, elite athletes, oxygen transport, VO2max

Abstract

Introduction. Based on available scientific literature, training at natural altitude has failed so far to prove useful for the enhancement of sea level performance in swimmers1,2. This controlled

1 This is a preliminary report of a paper submitted for publication to the Journal of Applied Physiology (January 2014)
nonrandomised four parallel groups trial examined the effects on performance, oxygen transport and total hemoglobin mass (tHb\textsubscript{mass}) of four training interventions: terrestrial living high-training high for 3 or 4 weeks (Hi-Hi3, Hi-Hi), living high-training high/low (Hi-HiLo), and living and training at sea level for 4 weeks (Lo-Lo).

**Methods.** From 65 elite swimmers, 54 met all inclusion criteria and completed sea-level time trials over 50 and 400 m front crawl (TT50, TT400), and 100 (sprinters) or 200 m (non-sprinters) at best personal stroke (TT100/TT200). \(V'O\textsubscript{2}\text{max}\) was measured on an incremental 4x200-m front crawl test. Training load was estimated using TRIMP and session RPE assessment. Initial performance and measures (PRE) were repeated immediately after the camp (POST) and once weekly on return to SL during 4 weeks. tHb\textsubscript{mass} was measured in duplicate at PRE and once a week during the camp. Intervention effects were analysed using mixed linear modelling.

**Results.** TT100 or TT200 improved by \(\sim 3.5\%\) regardless of living or training at sea level or at altitude, but Hi-HiLo improved more two (5.3±1.6\%) and four weeks (6.3±1.9\%) after the intervention as compared to the other groups. Hi-HiLo and Hi-Hi improved more in TT400 (4.6±1.4\% and 3.3±1.4\%, respectively). There were no changes in \(V'O\textsubscript{2}\text{max}\) in any of the groups after the intervention. tHb\textsubscript{mass} increased in Hi-Hi (6.2±2.6\%) and Hi-Hi3 (3.8±5.6\%), whereas no significant changes were noted in Hi-HiLo (1.3±4.3\%).

**Conclusions.** Hi-HiLo is an effective strategy to enhance performance in elite swimmers over a range of distances, clearly exceeding the smallest worthwhile enhancement effect for Olympic-standard swimmers (0.8–1\%)\(^3\). This substantial performance improvement was not linked to changes in \(V'O\textsubscript{2}\text{max}\) or tHb\textsubscript{mass}, hence could not be attributed to enhanced oxygen transport capacity.

**Introduction**

Altitude training (AT) has been matter of extensive research for half a century and it still plays an important role in the preparation of athletes in many countries\(^4,5\) despite the skeptical view of some investigators on its efficacy to enhance sea-level performance, particularly in elite athletes\(^6\). Despite being used by very many elite swimmers and coaches, there is a remarkable lack of controlled studies in swimming, and there is no evidence that training at natural altitude enhances performance more than training at sea level (SL)\(^1,2\). Even though in the last decade the Hi-Lo approach has largely supplanted classical AT in the scientific literature\(^5\), no studies have been conducted using this strategy in natural altitude in swimmers.

In view of the vast disconnect between research evidence and practical use of AT, particularly in elite swimmers, an international group of investigators conducted an international collaborative research study (The Altitude Project) to examine the impact of different current AT strategies on performance, technique, and health status of elite swimmers.

This study aimed 1) to contrast the hypothesis that living at moderate altitude (2,230 m) and training both at moderate and at lower altitude for four weeks (Hi-HiLo) improves SL swimming performance more than living and training at altitude (classical terrestrial AT) for 3 (Hi-Hi3) or 4 weeks (Hi-Hi), or than living and training at low altitude (conventional Lo-Lo sea-level training); 2) to elucidate whether the adaptive mechanisms conform with the ‘erythropoietic paradigm’ (i.e., are mainly hematologic in nature, via the activation of erythropoiesis by induced hypoxia, with subsequent increase in \(V'O\textsubscript{2}\text{max}\)); and 3) to quantify the eventual effect of the different interventions on performance on return to SL and to track changes during a lengthy period of 4 weeks without concurrent tapering.

**Methods**

This study is a controlled, nonrandomised, four parallel groups trial, comparing changes in swimming performance, \(V'O\textsubscript{2}\text{max}\) and tHb\textsubscript{mass} after an experimental intervention consisting of training camps in 4 different conditions: 1) living and training at moderate altitude (2,320 m) for 4 weeks (Hi-Hi); 2) identical intervention for 3 weeks (Hi-Hi3); 3) living at altitude and training at both moderate and low
altitude (690 m) for 4 weeks (Hi-HiLo); and 4) living and training near SL (190 or 655 m) for 4 weeks (Lo-Lo).

After a low intensity lead-in period all swimmers and their coaches travelled to Sabadell (190 m) or Madrid (655 m), Spain, where they stayed for 3-5 days for baseline testing. Next, all swimmers allocated to the AT groups (n = 43) travelled to the High Altitude Training Center (CAR) at Sierra Nevada (2,320 m), Spain, where they lived for 3 or 4 weeks. The two Lo-Lo sub-samples lived and trained in Sabadell (n = 10) and the High Performance Center (CAR) at Madrid (n = 7). One of the Hi-Hi3 subgroups (n = 6) was tested in Granada, Spain (690 m). In all cases, baseline and final testing were conducted at the same location and facility.

65 swimmers of both sexes (35 women and 30 men) were recruited from eight countries (AUS, BRA, CHI, GBR, NED, SLO, ESP, and TUN). Selection criteria included to have competed internationally during the previous season and/or being pre-selected as a member of their National and/or Olympic teams. Their competitive level was quantified using the FINA Point Scoring (FPS) system.

The primary outcome assessment was swimming performance, as measured in time trials (TT) on 100 m (sprinters) or 200 m (non-sprinters) at personal best stroke (TT100 or TT200). Secondary outcomes were \( V'O_{2\text{max}} \) assessed with a 4x200-m incremental swimming test and \( tHb_{\text{mass}} \). After warm-up, subjects swam 3x200 m crawl at paced speeds (F: 0.9, 1.0, and 1.1 m·s\(^{-1}\); M: 1.0, 1.1, and 1.2 m·s\(^{-1}\)). After 10 min of passive recovery, subjects completed an all-out 200 m swim to determine \( V'O_{2\text{max}} \) using a telemetric portable gas analyzer (K4 b\(^2\), Cosmed, Italy) connected to the swimmer by a low resistance respiratory snorkel. \( V'O_2 \) data were fitted by nonlinear regression and the maximal asymptotic \( V'O_2 \) amplitude was taken as the swimmer’s \( V'O_{2\text{max}} \) (TE = 3.1%; 95% CI: 1.1–5.1; n = 9).

\( tHb_{\text{mass}} \) was measured using the optimised CO-rebreathing method, as described by Schmidt and Prommer\(^{10} \) with some modifications (TE = 1.35% (95% CI: 0.10–2.65).

The study was carried out during the first macrocycle of the Olympic year prior to the London 2012 Olympics. Individualised training plans were developed by the swimmers’ personal coaches. HR monitors and beacon transmitters (CardioSwim, TX H\(_2\)O; Freelap, Switzerland) were used to register the lap times, rest intervals, and 50-m average speed. A modified TRIMP calculation suited for interval training was used to estimate the ‘cumulative TRIMP’ (TRIMPc)\(^{13} \). Each athlete kept a detailed training log which included self-administered questionnaires to assess session-RPE (s-RPE)\(^{14} \) and total state of fatigue (TSF-10). Iron supplementation was prescribed or strongly recommended to all swimmers at altitude based on their ferritin levels monitored weekly in all altitude groups during the intervention period.

All training camps were conducted in training centres of international standards, where subjects lived and trained as a group for the whole intervention period. In the recruiting phase, coaches were offered to choose among the 4 different interventions. To evaluate information bias of the intervention, two ad hoc questionnaires were administered to coaches and swimmers at the beginning and at end of training camp.

Effects on performance, \( V'O_{2\text{max}} \) and \( tHb_{\text{mass}} \) are expressed as percent change values (Δ%; ±90% CI)\(^{15} \). Correlation was assessed by the Pearson’s coefficients (r). In assessing the effect of the intervention on TT performance and \( tHb_{\text{mass}} \) over time the linear mixed modelling procedure (Proc Mixed, SAS, v. 9.1.3) for repeated measures was used to estimate means for main effects and group x test interaction, with Tukey’s post hoc pairwise multiple comparisons to identify the source of differences. An ANCOVA analysis was carried out using TRIMPc as a covariate for performance. To evaluate the effects of the intervention on \( V'O_{2\text{max}} \) a 2-tailed paired t-test was used.

**Results**

54 subjects (30 F, 24 F) successfully completed the intervention protocol of the original total of 65 subjects. After the intervention period, all coaches responded to the ad hoc questionnaire that they...
would have chosen again the same intervention, and that they expected that it would help the swimmers to improve their performance. On POST, the swimmers' answers to the latter question were 'yes' (91%), or 'not sure' (9%). These participants belonged to the Lo-Lo (n = 1), Hi-Hi (n = 2), and Hi-Hi3 (n = 3) groups. No subjects answered 'no'.

Daily average TRIMPc was greater in Hi-HiLo (258 ± 95) than in Hi-Hi (205±102; P = 0.01), Hi-Hi3 (177±115; P<0.001), and Lo-Lo (209±100; P=0.006). Mean daily s-RPE scores were greater in Hi-Hi3 (5.3±1.8), than in the other three groups (Hi-Hi: 4.4±1.9, P<0.001; Hi-HiLo: 4.8±1.6, P=0.01; and Lo-Lo: 4.2±1.8, P<0.001). Mean daily TSF-10 scores were also higher (P<0.001) in Hi-Hi3 (8.2±2.4), than in the other three groups (Hi-Hi: 6.8±2.1; Hi-HiLo: 6.2±1.7; and Lo-Lo: 6.3±2.9).

Relative percent changes in TT100 (sprinters) or TT200 (non-sprinters) time trial tests in the different groups are presented in Figure 1.

There were no changes in V'O_{2max} in either Lo-Lo (1.9%; ±1.5%), Hi-Hi3 (1.5%; ±2.5%), Hi-Hi (1.1%; ±2.6%), or Hi-HiLo (1.3%; ±1.4%). No relationship between change in V'O_{2max} and change in TT400 performance was found for the entire group of subjects (r=0.01, P=0.95) or for the swimmers in each group. Likewise, there was no relationship between changes in V'O_{2max} and changes in TT100 or TT200 performance, neither for all subjects (r=0.10, P=0.50) nor for each group.

Compared to PRE, increase in tHb mass was more pronounced in Hi-Hi group (at W4: 6.2%; ±1.1%; P<0.001) than in the Hi-Hi3 group (at W3: 3.8%; ±2.3; group x test interaction P=0.02), whereas no changes were found in the Hi-HiLo group (at W4: 1.3%; ±1.8; P=0.71). Changes in tHb mass and in V'O_{2max} were not associated neither for all subjects (r=0.01; P=0.96) nor for each group.
**Discussion**

To the best of our knowledge, this is the first investigation to show performance improvements after a terrestrial AT intervention using a controlled design in swimmers, and one of the few in truly elite athletes \(^5, 16, 17\).

Although the vast majority of studies in the AT literature are uncontrolled and underpowered especially with elite athletes \(^5, 6, 18\) —, there seems to be a growing consensus that when athletes are exposed to an adequate ‘dose’ of altitude exposure and training, the majority may improve endurance performance \(^4, 19-22\). In a recent meta-analysis, Bonetti and Hopkins \(^{18}\) concluded that changes in studies using the Hi-Hi approach were unclear, whereas changes using terrestrial Hi-Lo were considered likely both for elite and subelite athletes (~4%–5% from uncontrolled studies. These estimations are in line with a recent review that estimated that a 3-week terrestrial altitude camp would elicit mean performance improvements of ~1.8% (Hi-Hi) and ~2.5% (Hi-Lo) \(^5\).

The evidence in swimming is less compelling. Six uncontrolled studies have tested the Hi-Hi strategy in swimmers. Three of them were entirely negative \(^{23-25}\), and two others showed modest and statistically unclear improvements in performance of ~1.6–1.8% \(^{26, 27}\). In the only controlled study \(^{28}\), the small increase in performance in 100- and 200-m races (0.1–0.7%) was likely below the smallest worthwhile enhancement effect of the intervention \(^3, 29\).

Why should swimming be different from land-based endurance sports regarding AT effects? First, swimming performance is more dependent on economy (energy cost) than on maximal metabolic power \(^30, 31\); it follows that the benefit of enhanced metabolic capacity can be outweighed by impaired technique and economy. Second, the benefit of AT might be more or less potent for swimmers of different events.

A key factor in the individual response to training, whether at altitude or at SL, is the training load. When TT performance data were adjusted for TRIMPc, there remained significant between-group differences suggesting that not all of them could be attributed solely to training. Ultimately, the fact that the Hi-HiLo group achieved a greater training internal load, but not training effort, may be a core element of the Hi-HiLo training paradigm.

The remarkable improvement observed in swimming performance could not be attributed to enhanced \(\text{O}_2\)-transport capacity. Consistent with previous reports, we found that \(t\text{Hb}_{\text{mass}}\) clearly increased in those swimmers living and training at altitude for 3 (3.8%) or 4 weeks (6.2%). The magnitude, time course, and large variability of the erythropoietic response was in line with a recently published meta-analysis including data of 16 AT studies \(^{32}\). However, in contrast to the Hi-Hi groups, mean \(t\text{Hb}_{\text{mass}}\) did not change in our Hi-HiLo swimmers (at W4: 1.3; ±1.8%) who were also exposed to the same degree of sustained hypobaric hypoxia for 4 weeks. The simplest explanation for these contrasting results may be the individual variability in \(t\text{Hb}_{\text{mass}}\) changes, since half of the subjects actually showed an increase of \(t\text{Hb}_{\text{mass}}\) over the TE of the measurement. However, comparable results were found in elite track cyclists \(^{33}\), and in endurance athletes exposed to normobaric hypoxia \(^{34}\). We must consider also that a wide variability in the erythropoietic response to moderate hypoxia has been consistently shown \(^{32, 34-39}\).

In the present study, changes in \(t\text{Hb}_{\text{mass}}\) were not associated with changes in \(\text{V'O}_2\text{max}\). These results are in line with those reported in a recent review \(^{40}\) of 10 recent studies involving four different sports, which estimated a mean ~3% increase in \(t\text{Hb}_{\text{mass}}\) and \(\text{V'O}_2\text{max}\) and a similarly significant, albeit weak,
correlation between both parameters ($r^2 = 0.15$). It should be emphasised that this relationship between changes in tHb$_{\text{mass}}$ and V'\text{O}_2\text{max}$ after altitude exposure is somewhat lower than that observed after rhEPO administration (e.g. $r^2 = 0.28$) $^{40-42}$ emphasising that V'\text{O}_2\text{max}$ is a complex parameter that is not exclusively determined by the red cell mass $^{43}$.

The present study underpins the complex interaction among altitude acclimatisation effects (such as Hb$_{\text{mass}}$, among others), altitude and SL training effects, V'\text{O}_2\text{max}$, and performance in events of different sports and different durations/intensities requiring widely divergent metabolic demands $^{22, 36, 37, 44, 45}$. Despite failing to demonstrate an increase in tHb$_{\text{mass}}$ or V'\text{O}_2\text{max}$, the swimmers in the Hi-HiLo group clearly improved performance more than the altitude controls. Possible explanations include: a) swimming, especially in the shorter distances, may not be as dependent on oxygen transport as endurance running or cycling; b) there are other factors (e.g. differences in training intensity) that may have played a greater role in improving swimming performances through as yet undetermined mechanisms.

We were committed to recruit truly elite athletes. Working with such unique individuals in a real-word setting, particularly during an Olympic season, we were confronted with the virtual impossibility to conduct a fully controlled experiment without seriously compromising the ecological validity of the study or limiting its external validity. As subjects were not allocated randomly, selection bias may have occurred despite our attempt to minimise its likelihood by allocating swimmers from at least two different squads and nations in each intervention group, after assuring that the 4 experimental groups were properly matched for performance level, weight, height, V'\text{O}_2\text{max}$ and tHb$_{\text{mass}}$.

Practical Implications for Training and Performance. Swimming performance might be expected to substantially improve (~3.5%) as a result of a well-implemented coach-prescribed training camp, regardless of whether the camp is held at altitude (Hi-Hi) or not. However, a much greater benefit (~6.3%) can be expected using the Hi-HiLo strategy for 4 weeks. Mid-term swimming aerobic endurance performance (400 m) can be expected to improve more by living and training at altitude for 4 weeks than by living and training at SL, though the additional benefit is most likely to be larger using the Hi-HiLo (~3%) than the Hi-Hi strategy (~1.7%). Similarly, Hi-HiLo can be expected to improve sprinting capacity 1 to 3 weeks after the altitude camp (4.8–5.5%), the benefit being superior to any other intervention at the second week from return to SL. Care should be taken not to generalise these improvements to all swimmers, since substantial individual variability was noted in this as well as other studies $^{16, 35, 36}$. While performance can be stabilised or even worsened immediately on return from altitude, the greatest benefits are likely to be attained after 2 to 4 weeks after return to SL. This relatively long time interval could eventually be used to intensify training in the following few macrocycles and/or may provide a time window for tapering before competition. Monitoring individual training load and adaptation during and after the altitude camp to avoid excessive overload or detraining, as well as assessing individual peaking performance profile, are strongly recommended before applying these rules to individual cases.

Conclusion

Swimming performance of elite swimmers in 100- (sprinters) or 200-m (non-sprinters) improved significantly by ~3.1–3.7% in response to a coach-prescribed training camp whether at SL or at altitude. With 2 weekly sessions of high-intensity training at lower altitude (Hi-HiLo), a remarkably greater improvement was attained 2 (5.3%) and 4 weeks (6.3%) after the training camp. This substantial improvement was not linked to changes in V'\text{O}_2\text{max}$, oxygen kinetics or tHb$_{\text{mass}}$, hence could not be attributed exclusively to enhanced oxygen transport capacity. We conclude that: a) a well implemented training camp improves performance even in elite swimmers; b) living high-training low improves performance in swimming above and beyond altitude and SL controls, through complex mechanisms involving altitude living and SL training effects.
References


Effects of subacute moderate hypoxia on performance, peak oxygen uptake and stroke kinematics in 50- to 400-m time trials in elite swimmers

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Keywords: altitude, swimming, oxygen uptake, oxygen transport, biomechanics

Abstract

Introduction. Exposure to moderate hypoxia negatively impacts many physiological responses to maximal exercise (e.g. decreased cardiac output and muscle recruitment, increased cost of ventilation) and impairs aerobic performance, whereas short duration, anaerobic exercise is not much affected. The effect of acute hypoxia on physiological and technical performance in swimmers has not been investigated during submaximal1 but not during maximal swimming exercise. We analysed the effects of subacute exposure to moderate altitude within a range of distances on maximal swimming performance, peak VO2 and stroke kinematics in elite swimmers.

Method. Nine elite swimmers (8 M, 1 F) performed an incremental 4x200 m front crawl test (T4x200) for VO2max. On separate days, they performed time trials in a 50-m indoor pool: 50 and 400 m front crawl (TT50, TT400) and 200 m at best personal stroke (TT200). They were tested both under normoxic (NORM) and hypoxic conditions (HYPO) ~72 h after arrival to an altitude of 2,320 m (CAR Sierra Nevada, Spain). Respiratory gases were collected breath-by-breath for 1 to 3 min during the immediate recovery. Peak VO2 was taken as the first post-exercise 20-s average. Swim trials were video recorded with 3 lateral cameras (50 Hz), 2 placed underwater and 1 outside the water. Final time (t) and 3-cycle stroke rate (SR), stroke length (SL), and stroke index (SI) were assessed on each trial. Differences in peak VO2 measured in the different tests were assessed using ANOVA for repeated measures. Differences between NORM and HYPO were assessed using the two-tailed paired t-test (P<0.05 for significance).

Results. Under NORM conditions, there were no significant differences between VO2max (3,555 ± 827 ml·min−1) and VO2peak measured at TT50 (3,246 ± 732 ml·min−1), TT200 (3,341 ± 766), or TT400 (3,331 ± 648) (P=0.25). Under HYPO conditions, there were no differences in VO2peak measured at TT50 (2,955 ± 501 ml·min−1), TT200 (2,921 ± 524), or TT400 (2,856 ± 476) (P=0.59). When comparing measurements under NORM and HYPO conditions, there were not differences in TT50 in any of the parameters. In contrast, in TT200 and TT400 there was a decrease in performance (2.9 ± 1.6% and 1.2 ± 1.2%, respectively, mean ± SD), peak VO2 (12 ± 6% and 14 ± 10%), and SI (4.1 ± 3.8% and 5.8 ± 3.0%).

Conclusions. Acute exposure to moderate altitude (2,320 m) does not affect sprinting ability (~30 s), whereas it impairs middle-distance performance (~2-5 min), VO2peak, and stroking efficiency, likely as a consequence of early fatigue caused by centrally-limited O2 delivery to the exercising muscles.

Introduction

Exposure to moderate hypoxia negatively impacts many physiological responses to maximal exercise (e.g. decreased cardiac output and muscle recruitment, increased cost of ventilation) and impairs aerobic performance, whereas short duration, anaerobic exercise is not much affected. The effect of acute hypoxia on physiological and technical performance in swimmers has been investigated during submaximal1 but not during maximal swimming exercise. We analysed the effects of subacute exposure to moderate altitude within a range of distances on maximal swimming performance, peak VO2 and stroke kinematics in elite swimmers.
Methods

Nine elite swimmers (8 M, 1 F) performed an incremental 4x200 m front crawl test for VO$_{2max}$. On separate days, they performed time trials in a 50-m indoor pool: 50 and 400 m front crawl (TT50, TT400) and 200 m at best personal stroke (TT200). Swimmers were tested both at normoxic (NORM) and hypoxic conditions (HYPO) ~72 h after arrival to an altitude of 2,320 m above sea level (CAR Sierra Nevada, Spain).

Three testing sessions were conducted at sea level (190 m). At day 1, subjects performed an incremental 4x200-m test for VO$_{2max}$ (T4x200). First, after a ~30 min warm-up, they swam a 3x200 m front crawl at paced speeds (females: 0.9, 1.0, and 1.1 m·s$^{-1}$, males: 1.0, 1.1, and 1.2 m·s$^{-1}$). After 10 min of passive recovery, subjects completed an all-out 200 m swim to determine peak VO$_2$. VO$_2$ was measured using a telemetric portable gas analyzer (K4 b, Cosmed, Italy) that was held suspended over the water by an assistant following the swimmer along the pool with minimal intended interference with her or his swimming movements. This equipment was connected to the swimmer by a low resistance respiratory snorkel and valve system. On a preliminary analysis, VO$_{2max}$ was calculated from the 200-m maximal swim using 1) the nonlinear regression total amplitude for VO$_2$ ($A_0$), and 2) the last 20-s averaged values (3,450±711 vs. 3,364±713 ml·min$^{-1}$, respectively; $P=0.11$). Since both values were not significantly different, $A_0$ was then chosen to best represent the highest values attained during the maximal 200-m swim test and, thus, as the swimmer’s VO$_{2max}$. This approach was taken to minimise the impact of inter-breath and sampling time variability that has been observed when determining VO$_{2max}$ during a maximal 200-m swim, and based on the clear asymptotic stabilisation of VO$_2$ after the first half of the swim (~40-60 s in most cases) and at the final lap in all subjects. The reliability of VO$_{2max}$ measurements was characterised by a typical error (TE) of 3.1% (95% CI: 1.1–5.1; $n = 9$).

At day 2, after full warm up, 50-m (TT50) and 400-m (TT400) time trials were performed in the afternoon, allowing a recovery period of at least 60 min in between. At day 3, all swimmers performed a 200-m time trial (TT200). All tests were conducted at the same 50-m indoor pool (t: water 26–27ºC, air 27–28ºC). Respiratory gases were collected breath-by-breath for 1 to 3 min during the immediate recovery. Peak VO$_2$ (VO$_{2peak}$) was taken as the first post-exercise 20-s average.

Swimming time trials were video recorded with 3 lateral cameras (50 Hz), 2 placed underwater and 1 outside the water. Stroke rate (SR) and stroke length (SL) were calculated from the video records. Final time (t) and 50-m lap intervals (i) were measured for each time trial. Swimming average speed (v), which was determined in the midsection of the pool, was used in conjunction with the SR data to calculate the SL in each event lap and with this the SI, as follows:

\[
\begin{align*}
   v &= l_i \cdot t_i^{-1} \text{ (m·s$^{-1}$)} \\
   \text{SR} &= t_3^{-1} \cdot 60 \text { (cycles·min$^{-1}$)} \\
   \text{SL} &= v \cdot \text{SR}^3 \text { (m·cycle)} \\
   \text{SI} &= v \cdot \text{SL} \text { (m$^2$·s·cycle$^{-1}$)}
\end{align*}
\]

where $l_i$ = length (m) of midsections of lap $i$; $t_i$ = time (s) to cover the midsection of lap $i$; $t_3$ = time required to perform 3 stroke cycles was measured (Hz) transformed into cycle·min$^{-1}$ by multiplying by 60 (s·min$^{-1}$).

Values are presented as mean ± standard deviations (SD). The reliability of measurements was quantified using the typical error of measurement (TE = SD of difference scores/$\sqrt{2}$) expressed as a percentage of the mean ± 95% CI. Differences in VO$_{2peak}$ measured in the different tests were assessed using ANOVA for repeated measures (RM-ANOVA) with Bonferroni’s correction for multiple comparisons. Differences between NORM and HYPO for each variable were assessed using the two-
tailed paired t-test. Significance was set at $P<0.05$ for all analysis, which were conducted using PASW Statistics for Windows package, version 18.0 (SPSS Inc., Chicago, USA).

**Results**

Under NORM conditions, $VO_{2\text{max}} (3,555 \pm 827 \text{ ml}\cdot\text{min}^{-1})$ attained in the incremental T4x200 test was not significantly different from $VO_{2\text{peak}}$ measured at TT50 (3,246 ± 732 ml·min$^{-1}$), TT200 (3,341 ± 766), or TT400 (3,331 ± 648) (ANOVA-RM, $P=0.25$), suggesting a very fast increase in $VO_2$ even during the shortest distance. Similarly, under HYPO conditions, although $VO_{2\text{peak}}$ was consistently lower in all time trials, there were no substantial differences between the $VO_{2\text{peak}}$ measured after TT50 (2,955 ± 501 ml·min$^{-1}$), TT200 (2,921 ± 524), or TT400 (2,856 ± 476) ($P=0.59$).

When comparing measurements under NORM and HYPO conditions (Tables 1 and 2), performance was unaffected in TT50, as there were no differences in any of the performance, $VO_{2\text{peak}}$, and kinematic parameters. In contrast, both in TT200 and TT400 there was a decrease in performance (2.9% ± 0.9% and 1.2% ± 0.7%, respectively, mean ± 90% CI), paralleled by a decrease in $VO_{2\text{peak}}$ (-11.7% ± 3.3% and -13.5% ± 5.3%), and stroking efficiency (SI: -4.1% ± 2.1% and -5.8% ± 1.7%).

### Table 1

<table>
<thead>
<tr>
<th></th>
<th>TT50</th>
<th>TT200</th>
<th>TT400</th>
</tr>
</thead>
<tbody>
<tr>
<td>NORM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (s)</td>
<td>29.5 ± 1.7</td>
<td>135.8 ± 6.1</td>
<td>279.2 ± 9.3</td>
</tr>
<tr>
<td>Peak $VO_2$ (ml·min$^{-1}$)</td>
<td>3,246 ± 732</td>
<td>3,341 ± 766</td>
<td>3,331 ± 648</td>
</tr>
<tr>
<td>SR (cycles·min$^{-1}$)</td>
<td>49.6 ± 2.7</td>
<td>43.8 ± 5.0</td>
<td>40.9 ± 4.4</td>
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<tr>
<td>SL (m)</td>
<td>1.96 ± 0.12</td>
<td>1.98 ± 0.22</td>
<td>2.10 ± 0.25</td>
</tr>
<tr>
<td>SI</td>
<td>3.17 ± 0.34</td>
<td>2.83 ± 0.32</td>
<td>2.96 ± 0.42</td>
</tr>
<tr>
<td>HYPO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (s)</td>
<td>29.18 ± 1.64</td>
<td>139.7 ± 6.8*</td>
<td>282.5 ± 2.7*</td>
</tr>
<tr>
<td>Peak $VO_2$ (ml·min$^{-1}$)</td>
<td>2,955 ± 524</td>
<td>2,921 ± 524*</td>
<td>2,856 ± 476*</td>
</tr>
<tr>
<td>SR (cycles·min$^{-1}$)</td>
<td>49.5 ± 3.6</td>
<td>43.1 ± 5.4</td>
<td>40.7 ± 4.2</td>
</tr>
<tr>
<td>SL (m)</td>
<td>1.95 ± 0.13</td>
<td>1.96 ± 0.24</td>
<td>2.03 ± 0.23*</td>
</tr>
<tr>
<td>SI</td>
<td>3.13 ± 0.26</td>
<td>2.71 ± 0.36*</td>
<td>2.79 ± 0.37*</td>
</tr>
</tbody>
</table>

Data are mean ± SD. *Different from NORM (paired t-test, $P<0.05$)

The impairment in swimming performance was similar in TT200 and TT400 ($P=0.09$), whereas stroking efficiency (SI) was further impaired in TT400 (-5.8% ± 3.0%) compared to TT200 (-4.1% ± 3.8%) ($P=0.03$) (Table 2).

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>TT50</th>
<th>TT200</th>
<th>TT400</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYPO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (s)</td>
<td>-1.0 (± 1.2)</td>
<td>2.9 (± 0.9)*</td>
<td>1.2 (± 0.7)*</td>
</tr>
<tr>
<td>Peak $VO_2$ (ml·min$^{-1}$)</td>
<td>-7.3 (± 8.3)</td>
<td>-11.7 (± 3.3)</td>
<td>-13.5 (± 5.3)</td>
</tr>
<tr>
<td>SR (cycles·min$^{-1}$)</td>
<td>-0.2 (± 2.3)</td>
<td>-1.8 (± 1.6)</td>
<td>-0.2 (± 2.2)</td>
</tr>
<tr>
<td>SL (m)</td>
<td>-0.2 (± 2.1)</td>
<td>-1.3 (± 1.3)</td>
<td>-0.2 (± 2.2)</td>
</tr>
<tr>
<td>SI</td>
<td>-0.8 (± 2.5)</td>
<td>-4.1 (± 2.1)</td>
<td>-5.8 (± 1.7)*</td>
</tr>
</tbody>
</table>

Data are mean (± CI 90%). *Different from TT50 (RM-ANOVA, Bonferroni, $P<0.05$)

In TT200, differences in stroking efficiency (SI) between NORM and HYPO inversely correlated to $VO_{2\text{max}}$ ($r=-0.88$, $P=0.02$), meaning that in a 200-m time trial, those swimmers with lower $VO_{2\text{max}}$ tended to be those whose swimming efficiency was most impaired at altitude. A similar trend was observed in TT400 ($r=-0.52$, $P=0.15$). However, differences in swimming performance were not correlated to differences in $VO_{2\text{peak}}$ or SI in any of the time trial tests.
Discussion

Although substantial differences exist in the relative contribution of the three energy delivery systems during swimming between 50 and 400 m at maximal speed, our finding that VO$_2$max attained at the incremental T4x200 was similar to VO$_2$peak measured at any of the time trial tests confirms that VO$_2$ kinetics in swimmers are faster in the shorter distances, partially compensating for the relatively lesser contribution of oxidative metabolism. Despite the lower VO$_2$peak values attained at altitude, the same pattern was observed also in hypoxic conditions.

Swimming performance or stroke kinematics in 50-m time trial performance were unaffected by HYPO hypoxic conditions despite a substantial reduction (~7%) in VO$_2$peak. This outcome is consistent with a previous study in which performance during 30-s Wingate cycling tests in severe acute hypoxia was maintained or barely reduced owing to the enhancement of the anaerobic energy release.

In contrast, both in TT200 and TT400, performance was impaired (by 2.9% and 1.2%, respectively), in parallel with a very substantial decrease in peak VO$_2$ and stroking efficiency (SI decreased by ~4% and 6%). This pattern of responses is consistent with evidence of a linear decline in VO$_2$max during maximal running with altitude hypoxia, which was estimated to be a 6.3% (range 4.6–7.5%) decrease per 1,000 m increasing altitude, corresponding in our case (2,320 m) to an estimated decrease of ~11 to 17%, which fits well with the observed decrease in TT200 (11.7%) and TT400 (13.5%). This new finding shows that maximal performance in 200 and 400 m is mainly limited by moderate hypoxia, likely only partially compensated by the glycolytic energy sources. These findings are also consistent with previous results in which blood lactate and heart rate were higher in a 400-m test swum at moderate hypoxia (2,300 m) at ~93% of the maximal speed attained at an all-out 400 m test at near sea level (690 m).
The impaired stroking efficiency after acute exposure to hypoxia was characterised by a decreased stroke index in TT400 (-5.8%) and TT200 (-4.1%), paralleled by a decrease in stroke length in TT400 (Table 1–2). The changes in the stroke parameters partly depend on aerobic potential—more particularly, aerobic endurance. The extent to which the anaerobic metabolism is involved in total energy release also influences the changes in the swimming stroke. Swimmers have to maintain an optimal and elevated SL in spite of the emergence of fatigue, which tends to decrease the ability to develop the force necessary to overcome the resistance to forward movement. This notion is in line with the slight decrease in SL observed during swimming above the anaerobic threshold. The reduction of SL above the lactate threshold would be related in part to the accumulation of blood lactate, whereas SR would primarily be determined by the ability to maintain adequate neural activation.

The inverse correlation found between differences in stroking efficiency between NORM and HYPO in TT200 ($r = -0.88$), and perhaps also in TT400 ($r = -0.55$), suggests that the impact of exposure to acute hypoxia on stroke efficiency is greater in those swimmers exhibiting a lower VO$_{2\text{max}}$ in normoxia. This means that stroking efficiency would be less affected by acute exposure to altitude hypoxia in swimmers with a higher aerobic power.

Therefore, collectively, our findings clearly suggest that the impaired performance at altitude is mainly related to the limitations in aerobic capacity imposed by restricted oxygen delivery to the muscles as a direct result of environmental hypoxia.

Conclusions

Acute exposure to moderate altitude (2,320 m) does not affect sprinting ability (~30 s, 50 m), whereas it impairs maximal middle-distance swimming performance (~2 to 5 min, 200 and 400 m), VO$_{2\text{peak}}$, and stroking efficiency, likely as a consequence of early fatigue caused by centrally-limited O$_2$ delivery to the exercising muscles.

References


**Lactate parameters and 100m freestyle results in male and female youth swimmers**

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**Keywords:** 100m freestyle, lactic acid, youth swimmers

**Abstract**

The aim of the present study was: a) the correlation between lactate parameters and 100m freestyle results and b) differences between blood lactate recovery parameters between genders in youth swimmers. The sample of this study consisted of 20 swimmers, of them 10 were male of age=16±1 y, height 180±5 cm and mass 70±8 kg and 10 were female of Age=16±0.5 y, height=168±7 cm and mass=59±5 kg. Subjects performed 100m freestyle with maximum intensity (100\textsuperscript{V\textsubscript{EL}}). Performance time was recorded and heart rate (HR) recorded after the test. For the determination of maximum accumulation of lactic acid (La\textsubscript{MAX}), blood capillary samples were taken in 3rd, 5th and 7th min post-exercise. The results of this study showed that there is statistical significant relationship between 100\textsubscript{V\textsubscript{EL}} and timecourse of blood lactate recovery parameters as predictor variables at R\textsuperscript{2}\textsubscript{adj} = 0.97, Standard Error = 0.68, p = 0.000. Statistically significant differences between male and female swimmers was only found at: t\textsubscript{La\textsubscript{MAX}} = 1.982, p=0.039 (347.4±72.4 vs 261.8±87.2 sec for male and female swimmers to reach Mac Lactate, respectively).

**Introduction**

Maximal performances in swimming depend on the maximal metabolic power of the athlete and on the economy of locomotion. The amount of metabolic energy spent in transporting the body mass of the subject over a unit of distance has been defined as the energy cost of locomotion (Di Prampero 1986). A significant amount of energy is derived from anaerobic energy release. The amount of anaerobic energy depends on the distance and velocity at which swims are performed (Strumbelj 2002).

Diagnosing in swimming is the process which is focused on the evaluation of the preparedness of the athletes in relation to the training load as much as other various factors, in order to control the training process (Korcek 1992). This process is continuous and intentional so that it the effectiveness of the training process can be improved. The response of the organism to the training load thus provides the information about the athlete’s preparedness. The utility of assessing [BLa] for swimmers is important of a variety of training a and competitive purposes (Vescovi et al. 2010).

In competitive swimming, coaches and swimmers need to achieve more efficient and faster swim speeds, using data such blood lactate accumulation in muscles to improve high speed endurance during swim training (Olbrecht 2000; Nomura & Shimoyama 2002). Competitive swimming events consist of different distances from 50m to 1500m and it takes approximately 23 seconds to 14 minutes 30 seconds to complete swimming those distance events (Olbrecht 2000; Ogita 2006). Short
duration bouts of high intensity exercise rely largely on non-oxidative energy metabolism, resulting in the accumulation of muscle and blood lactate [BLa] (Di Prampero 1986; Strumbelj 2002).

Peak blood lactate concentration for swimming events could be an indicator of swimming effort, especially if the race is fast as it occurs following swimming competitions. Provided the competition does not last significantly longer than 2 min, the necessary energy is provided mainly through the lactic anaerobic system (Elliott & Haber 1983). Peak [BLa] concentration following maximal exercise has a direct relationship with performance in swim events ranging between 100m and 800m (Olbrecht 2000). The highest lactate levels have been recorded following the swimming distances of 100m and 200m (Vescovi et al. 2010).

Review of the scientific literature revealed that peak blood lactate levels are not significantly different between the two genders (Chatard 1988; Jacobs 1983), suggesting that the capacity to produce high lactate levels in the blood is probably acquired through training (Avlonitou 1996).

The aim of the present study was: a) the correlation between lactate parameters and 100m freestyle results and b) differences between blood lactate recovery parameters the two genders at youth swimmers.

**Methods**

**Sample**

The sample of this study consisted of 20 swimmers, all active short and middle distance swimmers, of them 10 were male of Age=16±1, BH=180±5 and BW=70±8 and 10 were female of Age=16±0.5, BH=168±7 and BW=59±5. The test took place in an open swimming pool of 50m during the precompetitive phase of summer period. After a standardised warm up of 600m with the guidance of the coach and 10 minutes of rest, subjects performed 100m freestyle with maximum intensity (100\textsubscript{V\textsc{el}}) as a criteria variable.

**Variables**

Performance time in each 50m was recorded. Heart rate (HR) was estimated the first 10 seconds after the test. Blood capillary samples were taken in in 3rd, 5th and 7th min post exercise in order to determine the maximum accumulation of lactic acid ($\text{La}_{\text{max}}$) and were analysed with the portable analyzer SCOUT LACTATE GERMANY. The seven following variables were used as blood recovery lactate parameters:

1. $\text{La}_{\text{P\textsubscript{EAK}}}$, blood lactate concentration at zero time after the 100 m all-out trial, estimated using the backward method from polynomial mathematical equation, expressed in mmol/L;
2. $\text{La}_{\text{max}}$, maximal blood lactate concentration in recovery period of time after the 100 m all-out trial, estimated from polynomial mathematical equation method, expressed in mmol/L;
3. $t_{\text{La}_{\text{max}}}$, time needed to reach maximal blood lactate concentration in recovery period of time after the 100 m all-out trial, estimated from polynomial mathematical equation method, expressed in sec;
4. Index $\text{La}_{\text{P\textsubscript{EAK}}}/100\text{\textsubscript{V\textsc{el}}}$, index calculated as relation between blood lactate concentration peak value and 100 m all-out bout average velocity, expressed as index value;
5. Index $\text{La}_{\text{max}}/100\text{\textsubscript{V\textsc{el}}}$, index calculated as relation between maximal blood lactate concentration value and 100 m all-out bout average velocity, expressed as index value;
6. Index $\text{HR}/\text{La}_{\text{P\textsubscript{EAK}}}$, index calculated as relation between blood lactate concentration peak value and heart rate measured 10 seconds after 100 m all-out bout average velocity, expressed as index value;
7. Index HR/LaMax, index calculated as relation between maximal blood lactate concentration value and heart rate measured 10 seconds after 100 m all-out bout average velocity, expressed as index value.

All mentioned above variables served as a sets of predictive variables. Multiple regression analysis (MRA) was used for the determination of relation between criteria and set of predictor variables. ANOVA and Student’s t test we used for gender differences calculations.

**Results**

The results of MRA showed that at general level there is statistical significant relationship between 100v100 and system of predictor variables at $R^2_{adj} = 0.9762$, Standard Error = 0.6853, $F_{ANOVA of Regression} = 83.01$, $p = 0.000$ (Table 2). At partial level only two variables are statistically significantly related with 100v100 as well as: LaMax – $t = -6.21$, $p = 0.000$, and Index LaMax/100v100 – $t = 4.78$, $p = 0.002$. Concerning the gender differences (Table 1), only statistically significant differences between male and female swimmers was found at: $t_{LaMax} = 1.982$, $p = 0.039$ (347.4±72.4 vs 261.8±87.2 sec for male and female swimmers, respectively).

**Table 1**  Values in means and SD in analysed variables

<table>
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<tr>
<th>100m free</th>
<th>100m Time</th>
<th>LaPeak</th>
<th>LaMax</th>
<th>LaMax_t</th>
<th>LaPeak/100v100</th>
<th>LaMax/100v100</th>
<th>HR/LaPeak</th>
<th>HR/LaMax</th>
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<tbody>
<tr>
<td>Male</td>
<td>58,83±2,33</td>
<td>7,18±2,27</td>
<td>8,75±1,03</td>
<td>347±72*</td>
<td>5,16±0,70</td>
<td>4,24±1,63</td>
<td>5,16±0,70</td>
<td>27,84±8,52</td>
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<tr>
<td>Female</td>
<td>66,17±2,79</td>
<td>6,82±2,35</td>
<td>7,77±1,14</td>
<td>262±88*</td>
<td>5,13±0,71</td>
<td>4,48±1,49</td>
<td>5,13±0,71</td>
<td>29,54±11,01</td>
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</tbody>
</table>

*Statistical significant difference between gender

**Table 2**  Multiple regression statistics

<table>
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<tr>
<td>Multiple R</td>
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<tr>
<td>LaPeak/100v100</td>
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<tr>
<td>HR/LaPeak</td>
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</tbody>
</table>

**Conclusion**

The results of multiple regression analysis showed that there is general statistically significant correlation between the predicted variable in relation to performance time in 100m freestyle swimming and blood lactate parameters in recovery after the test in the level of $R^2_{adj} = 0.9762$,.
Standard Error = 0.6853, F_{ANOVA} of Regression = 83.01, p = 0.000 (Table 2). At partial level only two variables are statistically significantly related with 100V as well as: La\_Max – t = –6.21, p = 0.000, and Index La\_Max/100V – t = 4.78, p = 0.002 (Table 2). This specific model has very small level of error of the predicted variable of the achieved result in 100m freestyle and this only ±0.6853sec.

In individual case, the correlation of this criteria and of the predicted variable validates that there is inversely proportional relation (negative) between the criteria that is performance time in 100m and maximum accumulation of lactic acid in blood, a fact that shows that the smaller the time of 100m freestyle the higher level of blood lactate concentration. This is expected because swimming intensity in 100m freestyle energetically depends on the development of glycolytic procedures, that means from the development of anaerobic lactic mechanism of swimmer (Olbrecht 2000; Rodriguez & Mader 2002; Strumbelj et al. 2002; Vescovi et al. 2010).

However, the results showed that La\_Max/100V has statistically significant correlation to the results in 100m freestyle swimming and with proportional positive relation (t = 4.78, p = 0.002). In other words, as higher is the velocity in 100m freestyle (higher swimming intensity achieved in specific distance) so are the changes in the values of this index. Generally we observe that this index presents the relationship between maximum concentration of lactic acid and swimming velocity in 100m freestyle and numerically expresses how much blood lactate accumulation is achieved in stable swimming velocity from 1m/sec. That means that a swimmer has low blood lactate concentration in stable velocity of 1m/sec. These values show that for the same value of maximum accumulation of lactic acid, the distance of 100m freestyle can be swim with higher intensity. Such results can prove that the determination of this index has measurable ability to be important index of metabolic efficiency in swimming in relation to the distance of 100m and this fact of course must me confirmed in next researches.

At general level, we can conclude that the test of 100m freestyle can be simple and useful tool to estimate the swimmers blood lactate recovery characteristics (Olbrecht 2000). It’s mean that one trial all-out 100m freestyle testing could be useful and simply method to checking the swimmers lactate characteristics at high intensity anaerobic specific strain. The results showed that variables as well as La\_Max and Index La\_Max/100V could be useful measurements for those detecting, regardless to gender at youth age.

References
Concurrent validity of a new model for estimating peak oxygen uptake based on post-exercise measurements and heart rate kinetics in swimming

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Keywords: swimming, oxygen uptake, extrapolation, heart rate, kinetics

Abstract

Introduction. We aimed to assess the validity of a mathematical model based on heart rate (HR) and post-exercise \( \dot{V}O_2 \) measurements for estimating peak \( \dot{V}O_2 \) at the end of a swimming exercise. Its physiological rationale relies on the assumption that during the immediate recovery the systolic volume and the arterio-venous \( O_2 \) difference remain practically constant for a certain period. According to Fick’s principle, this leaves HR as the main parameter for changes in \( \dot{V}O_2 \).

Method. 34 elite swimmers performed 3x200 m at increasing sub-maximal speeds, followed by a maximal 200 m swim. \( \dot{V}O_2 \) was measured breath-by-breath using a portable gas analyser (K4 b7, Cosmed) connected to the swimmer by a respiratory snorkel. HR was measured from RR intervals (CardioSwim, Freelap). Data were time aligned and 1-s interpolated. Exercise \( \dot{V}O_2 \) was the average of the last 20 s during the swim \( \dot{V}O_2(\text{end}) \), and recovery \( \dot{V}O_2 \) was the post-exercise first 20 s average \( \dot{V}O_2(0-20) \). The model calculates a virtual \( \dot{V}O_2 \) at time (t) of recovery \( \dot{V}O_2(t) \), using the quotient between the peak HR during the last 10 s of the swim \( HR(0) \) and the 1-s interpolated value at (t) \( HR(t) \), multiplied by the 1-s interpolated \( \dot{V}O_2 \) value at (t) \( \dot{V}O_2(t) \), resulting in: \( \dot{V}O_2(t) = HR(0) / HR(t) \cdot \dot{V}O_2(t) \). Average \( \dot{V}O_2 \) values were calculated for different time intervals and compared to measured exercise \( \dot{V}O_2 \) values (RM-ANOVA, post-hoc Tukey, \( *p<0.05 \)). Mean differences (mean ∆) and Pearson’s coefficient of determination (\( R^2 \)) were also calculated.

Results. Peak \( \dot{V}O_2 \) at the last 20 s during exercise (3547± SD 692 ml-min\(^{-1}\)) was different from \( \dot{V}O_2(0-20) \) (3431 ± 685) (mean diff. -116, 3.3%, \( p=0.001 \)). All virtual \( \dot{V}O_2 \) values were highly correlated with \( R^2 = 0.86 \) to 0.96, \( p<0.001 \), and not different from \( \dot{V}O_2(\text{end}) \). Best estimates (mean diff.<0.5%) were delivered by \( \dot{V}O_2(0-20) \) (3564 ± 698, \( R^2 = 0.96 \), SEE = 120) and \( \dot{V}O_2(5-20) \) (3559 ± 705, \( R^2 = 0.94 \), SEE=121).

Conclusions. The difference between peak \( \dot{V}O_2 \) at the end of the exercise and during the immediate recovery pinpoints the inaccuracy of the 20-s recovery method of estimation and supports the need for the model. The lack of significant differences and high correlation between measured peak \( \dot{V}O_2 \) and estimated post-exercise \( \dot{V}O_2 \) support its basic physiological assumption. In conclusion, the proposed mathematical model for estimating peak \( \dot{V}O_2 \), which couples and takes into account both HR and \( \dot{V}O_2 \) off-kinetics, provides valid and accurate results, while allowing the subjects to swim completely unimpeded and avoiding the uncertainty of the backward extrapolation method.
**Introduction**

The assessment of cardiopulmonary gas exchange and oxygen uptake (\(\dot{V}O_2\)) in swimming is a complex and cumbersome procedure and still faces limitations imposed by the environment and the equipment. There are two different approaches to measure in the water. The first one measures \(\dot{V}O_2\) online with a snorkel system connected to the swimmer\(^3\,\,^3\). The second one uses post-exercise measurements with gas collection via face or mouth masks connected to Douglas bags\(^4\) or open-circuit metabolic carts\(^5\).

However, the use of swimming snorkels modifies the biomechanical pattern when swimming both during incremental\(^6\) and 100-m maximal tests\(^7\) probably due to the increase of both passive and active drag imposed by the snorkel. In all these studies swimmers performed the tests in front crawl because of a stable head position. The impossibility to execute diving starts and conventional turns is also an important limitation. To overcome these problems, Montpetit et al. applied the backward extrapolation (BE) of the oxygen recovery curve, first used by di Prampero et al.\(^8\), to compare peak \(\dot{V}O_2\) values (\(\dot{V}O_{2\text{peak}}\)) during a multistage free swimming test using the Douglas bag technique with those estimated by the BE method during recovery after the same tests, as well as with those obtained during uphill treadmill running\(^9\). In 400-m maximal test, Lavoie et al.\(^9\) found an overestimation of \(\dot{V}O_{2\text{peak}}\) of 20%. Costill et al.\(^10\) found similar results using a single 20-s post-exercise collection of expired gas after a 366 m (400 yd) breaststroke swim, and found a decline in \(\dot{V}O_2\) causing a 16% overestimation of \(\dot{V}O_{2\text{peak}}\) during 7 min of tethered swimming.

A further development was using breath-by-breath measurements during the immediate recovery phase\(^11,\,\,12\). This new method confirmed the \(\dot{V}O_2\) delay at the onset of the decline of the recovery curve by identifying a plateau in many, but not all, swimmers, with a remarkable individual variability. It also revealed the cause for the overestimation of the classical BE method and defined a zone of uncertainty during the immediate recovery phase\(^13\).

Recently, our group developed a mathematical model based on heart rate (HR) and post-exercise \(\dot{V}O_2\) measurements for estimating \(\dot{V}O_{2\text{peak}}\) at the end of a swimming exercise which has been implemented\(^14\). The model is based on Fick’s principle, stating that respiratory \(\dot{V}O_2\) is a product of HR, stroke volume (SV) and arterio-venous oxygen difference (avDO\(_2\)). A model of venous return by Drescher et al.\(^15\) assumes no recognizable effects of avDO\(_2\) on respiratory \(\dot{V}O_2\) in the first seconds of recovery. Therefore, we take the assumption that SV in the immediate recovery of a swimming exercise remains constant. This assumption is related to the effect of immersion on SV\(^16\). This leads to a new model of calculation of a virtual \(\dot{V}O_2\) (\(\dot{V}O\_v\)) based on HR kinetics and post-exercise \(\dot{V}O_2\) measurements.

The aim of the present study was to assess the validity of this model by comparing the predicted values with directly measured values during maximal swimming exercise. Furthermore, different recovery intervals for \(\dot{V}O_2\) calculation are compared to find limitations for the practical use of the model.

**Methods**

34 elite swimmers (18 female and 16 male, 21.4 ± 3.7 years old, height 179.6 ± 90 cm, weight 72.1 ± 10.5 kg) performed an incremental 4x200-m test for \(\dot{V}O_{2\text{max}}\) (T4x200). First, after a ~30 min warm-up, they swam a 3x200 m front crawl at paced speeds (females: 0.9, 1.0, and 1.1 m·s\(^{-1}\), males: 1.0, 1.1, and 1.2 m·s\(^{-1}\)). After 10 min of passive recovery, subjects completed an all-out 200 m swim to determine peak \(\dot{V}O_2\). \(\dot{V}O_2\) was measured using a telemetric portable gas analyzer (K4 b\(^7\), Cosmed, Italy) that was held suspended over the water by an assistant following the swimmer along the pool with minimal intended interference with her or his swimming movements. This equipment was connected to the swimmer by a low resistance respiratory snorkel and valve system\(^17,\,\,18\). HR was continuously measured during exercise and recovery using beat-by-beat monitors (CardioSwim, Freelap, Fleurier, Switzerland). After the end of the exercise the swimmers remained in an upright
position immersed up to the neck while gases were collected during 3 min using a Hans-Rudolph 7400 (USA) oro-nasal mask applied immediately at the end of the swim, having instructed the swimmers to avoid expirations before the mask was placed at their arrival. For analysis, beat-by-beat HR and breath-by-breath $\dot{V}O_2$ data were synchronised to $t=0$ and 1-s interpolated. This study only deals with the data of the maximum swim.

Exercise $\dot{V}O_2$ was the average of the last 20 s during the swim ($\dot{V}O_2$(end)), and recovery $\dot{V}O_2$ was the post-exercise first 20-s average ($\dot{V}O_2$(0-20)). The model calculates a virtual $\dot{V}O_2$, at time (t) of recovery ($\dot{V}O_2$(t)), using the quotient between the peak HR during the last 10 s of the swim [HR(0)] and the 1-s interpolated value at (t) [(HR(t)), multiplied by the 1-s interpolated $\dot{V}O_2$ value at (t) [ $\dot{V}O_2$(t)]], resulting in:

$$ v\dot{V}O_2(t) = \frac{HR(0)}{HR(t)} \times \dot{V}O_2(t) \tag{1} $$

Average values were calculated for different time intervals (0-20 s, 5-20 s, 10-20 s, 15-20 s, and 10-15 s) (Figure 1), and compared to measured exercise $\dot{V}O_2$ as criterion values using ANOVA for repeated measures (RM-ANOVA) and post hoc Tukey’s test for multiple comparisons. Data are mean and standard deviations (±SD). Mean differences (mean Δ) are also indicated. Pearson’s coefficient of determination ($R^2$) was used to assess correlation. Significance was set at $P<0.05$.

![Figure 1](image)

Note: the red line (triangles) depicts the behaviour of the calculated (virtual) $v\dot{V}O_2$ according to equation [1].

**Figure 1** Heart rate (HR) and $\dot{V}O_2$ kinetics in the last 30 s of the exercise and the first 40 s of recovery during a 200 m maximal swim

**Results**

Table 1 shows the peak $\dot{V}O_2$ measured during exercise and recovery, as well as the calculated (virtual) $v\dot{V}O_2$peak values.
Discussion

The main finding of this study was that the new mathematical model based on heart rate kinetics and post-exercise $\dot{V}O_2$ measurements during maximal swimming exercise is a valid procedure of estimating peak $\dot{V}O_2$ in competitive swimmers. We also found that estimated peak $\dot{V}O_2$ from 20-s measurements during recovery underestimate exercise values, due to the time delay occurring at the onset of the $\dot{V}O_2$ recovery curve.

The low mean difference of $\Delta \dot{V}O_2(0-20)$ and the high correlation to exercise $\dot{V}O_2$ strengthens the validity of the physiological assumptions of the model. $\dot{V}O_2$-Off kinetics are virtually parallel to HR-off kinetics during the first 20 s of recovery. This indicates that there are no remarkable changes in avDO$_2$ and SV in this time period. Because the subjects remained immersed up to the neck for the whole recovery period, only little changes in SV were expected. In none of the subjects we could surmise a fall in SV in the immediate recovery. Some subjects showed a little rise in $\dot{V}O_2$ while HR remained constant immediately after, which can be interpreted as a rise in SV. This can be explained by the change in body position from horizontal to vertical; the lower part of the body is now deep immersed and under higher hydrostatic pressure, which increases venous return compared to a horizontal body position. This was likely the reason for the overestimation of $\Delta \dot{V}O_2(5-15)$ and $\dot{V}O_2(10-15)$. Because of the distance between muscle and mouth, remarkable changes in avDO$_2$ in the first seconds of recovery are not to be expected as shown by Drescher et al.\textsuperscript{15}, which is in agreement with the present results. As shown in Figure 1, $\Delta \dot{V}O_2$ does not decline for the first ~20 s during the immediate recovery, which is likely the time for the onset of avDO$_2$ changes perceivable in the exhaled air. To better support our two assumptions future studies investigating cardiac output (CO) kinetics after maximal swimming exercise would be required.

The low mean difference and the high correlation between exercise $\dot{V}O_2$peak and $\Delta \dot{V}O_2(5-20)$ agree with the findings of Rodriguez\textsuperscript{13} showing a plateau after maximal swimming exercise. Our results show that this plateau is likely the reason for the 20% overestimation of $\dot{V}O_2$peak found by Lavoie et al. after a maximal 400-m swim\textsuperscript{8}, and the 16% overestimation found by Costill et al. using a single 20-s post-exercise collection of expired gas after a 400- yd breaststroke swim\textsuperscript{10}. In fact, the time delay of the recovery curve at the onset of supramaximal exercise had been previously reported after exhaustive treadmill running\textsuperscript{8,19}, and after a 400-m swim at maximal speed using the same breath-by-breath post-exercise measurements as in the current study\textsuperscript{15}. Compared to the last procedure, the new model has the advantage of overcoming the uncertainty of the measurements during the first seconds of recovery, which can easily be affected by irregular breaths or noisy breath-by-breath signal.

Table 1  Peak $\dot{V}O_2$ measured during the last 20 s of exercise (criterion values), during the first 20 s of recovery, and estimated (virtual) peak $\dot{V}O_2$ calculated according to equation [1] at different time intervals

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Mean ± SD (ml·min$^{-1}$)</th>
<th>Mean Δ (ml·min$^{-1}$)</th>
<th>$R^2$</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exercise $\dot{V}O_2$\textsuperscript{peak}</td>
<td>-20</td>
<td>3547 ± 692</td>
<td>Criterion</td>
<td>–</td>
</tr>
<tr>
<td>Recovery $\dot{V}O_2$\textsuperscript{peak}</td>
<td>0-20</td>
<td>3431 ± 685</td>
<td>-116</td>
<td>0.959</td>
</tr>
<tr>
<td>Estimated ($\Delta \dot{V}O_2$\textsuperscript{peak})</td>
<td>0-20</td>
<td>3564 ± 698</td>
<td>17</td>
<td>0.963</td>
</tr>
<tr>
<td></td>
<td>5-20</td>
<td>3559 ± 705</td>
<td>13</td>
<td>0.943</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>3520 ± 725</td>
<td>-27</td>
<td>0.900</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>3438 ± 722</td>
<td>-109</td>
<td>0.856</td>
</tr>
<tr>
<td></td>
<td>5-15</td>
<td>3623 ± 707</td>
<td>76</td>
<td>0.963</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>3604 ± 731</td>
<td>57</td>
<td>0.923</td>
</tr>
</tbody>
</table>

Note: Mean differences ($\Delta$), Pearson’s coefficient of determination ($R^2$) and P-value (RM-ANOVA, Tukey, *p< 0.05) of the differences compared to the criterion values are shown.
From a technical standpoint, three conditions are required to ensure the validity of the results: 1) obtaining quality beat-by-beat HR recordings, 2) obtaining the first $\dot{V}O_2$ values as fast as possible avoiding missing breaths and hyperventilation, and 3) monitoring HR and $\dot{V}O_2$ during a recovery period of at least 20 s to avoid over- or underestimation. The use of waterproof beat-by-beat HR monitors is of paramount importance. In this respect, the monitors we use in our studies in the aquatic environment (CardioSwim, Freelap, Switzerland) cannot be considered as completely reliable. The breast electrodes, which can be securely placed using the elastic bands and the insulated wires, which act also as shoulder belts, do not always avoid the displacement of the electrodes, particularly in men. Although some improvements need to be made, also in the data transfer hard- and software, they are, to our knowledge, the most useful instruments for underwater HR monitoring. Another important issue in our practical experience is the need to instruct the subjects in order to avoid alterations in their normal breathing pattern during the recovery period, particularly during the first breaths. They should exhale the first breath immediately after touching the wall and not hyper- or hypo-ventilate to avoid spuriously high ventilation and, hence, $\dot{V}O_2$ values.

**Conclusion**

In conclusion, based on previous studies and current results, we propose the new model, based on post-exercise $\dot{V}O_2$ measurements and heart rate kinetics after a maximal swimming exercise, as a valid and accurate procedure of estimating peak $\dot{V}O_2$ in competitive swimmers. The new procedure overcomes the limitations imposed by the equipment used to measure $\dot{V}O_2$ during swimming, avoids over- and underestimation when using post-exercise $\dot{V}O_2$ measurements alone, and allows the subject to swim completely unimpeded and, hence, to achieve the full use of high-speed swimming technique and the specifically trained muscle mass in pool conditions.

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Comparing methods for summarising a training load in prediction models of swimming performance

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Keywords: elite swimming, longitudinal data, performance, statistical machine learning, training load intensities, training measurement

Abstract

Introduction. Training quantifications are valuable for monitoring and prescribing elite swimmers’ training and are indispensable in mathematical models that attempt to accurately predict performance. Modelling the association of training with performance raises an important issue: how should we account for volumes at different training intensities? Mujika et al. (1996) constructed a training load by adding weighted (by a priori constants representing energetic intensities) volumes from each intensity. Avalos et al. (2003) computed a training load as the sum of normalised training intensities. Here we compared the predictive accuracy of these methods to others based on: a/ alternative normalisations, b/ summary scores derived from data, and c/ machine learning techniques, with recognised predictive qualities, such as PLS.

Methods. Training volumes at eight intensity levels (in kilometres and minutes per week, for in-water and dry-land workouts, respectively) and performances in competition of 138 professional French swimmers were collected during 20 seasons. Training intensities were determined using measurements of blood lactate concentrations. We assumed that swimmers may react differently to the same training and over time, thus we used mixed-effects models adjusted for sex, age, swimming distance and event specialty. The comparison criterion was the cross-validated prediction error.

Results. Summary scores for three training loads (low-intensity/high-intensity/dry-land workouts) with data derived weights showed the best results (mean cross-validated prediction error ± SD were 0.60±0.89, 0.50±0.62 and 0.10±0.19 for sprint, mid- and long-distances, respectively). However, cross-validated prediction errors were close relative to their variances, which were high.
Conclusions. The use of complex machine learning techniques did not lead to more accuracy in predicting performance. Although data derived scores showed the lowest prediction error, the statistical variability was too high for being conclusive. A possible explanation is that the lactate sensitivity to extraneous factors (mode of exercise, technique quality of training, diet or sleep quality prior to test) and the subject-specific variations in lactate thresholds introduce not negligible measurement error. As practical recommendation, we suggest completing lactate measurements with athlete/coach questionnaires to better assess the physiological stress associated with the training load. Also, errors-in-variables models might be more appropriated.

Introduction
Achieving optimal performance in swimming implies developing and improving metabolic processes (the phosphagen, glycolytic and aerobic systems), muscular strength and endurance qualities, and technical skills through training. Training quantifications (the frequency, duration, intensity and type of exercise) provide valuable information to coaches and swimmers for monitoring and prescribing training. On the other hand, quantifications are indispensable in mathematical models that attempt to accurately predict performance and, thus, be used as a tool in the organisation of the athlete’s training program.

A few models have been proposed in the literature to study the training-performance relationship. The Banister’s model and its variations use antagonistic transfer functions representing the positive effects of training (leading to an increase in performance) and the negative effects (leading to short- or long-term fatigue and having a negative influence on performance). These models, close to those used in other fields that focus on the study of dose-response relationships (such as pharmacokinetics/pharmacodynamics) have been widely used in swimming (Banister et al. 1975; Busso et al. 1994, 2003; Mujika et al. 1996). Fitting these models involve, however, some statistical problems: since there is a model per subject, a considerable number of observations per swimmer is needed to fit each model, which is unusual in non experimental studies. Also, the model structure (symmetric antagonistic functions all estimated from the same training information), leads to large confidence intervals and unidentifiable parameters (i.e., severe parameters correlation) avoiding their biological interpretation (Hellard et al. 2006). Lastly, estimation is performed assuming independence of observations, however, performances closer in time may correlate, in which case, inference may be invalid. To address these problems, Avalos et al. (2003) proposed using mixed effects regression models that include I/the usual fixed effects for the dependent variables, thus, the effects common to the population are estimated using all the data; II/ the random effects that allows taking into account individual heterogeneity; and III/the residual structure that allows taking into account that data may be correlated within subjects.

Modelling the association of training with performance in swimming raises another important issue: how should we account for volumes at different training intensities? Mujika et al. (1996) constructed a training load by adding weighted intensity training volumes by a priori constants representing energetic intensities. Avalos et al. (2003) computed a training load as the sum of individually normalised (expressed as a percentage of the individual maximum) training intensities. Both approaches used measurements of blood lactate concentrations to determine training intensities. These methods aimed to scale training volumes from different intensities or modes (in-water kilometres, dryland minutes) in such a way that their values lie within a comparable range. These approaches circumvent problems of dealing with a large number of correlated training variables. Consequently, statistical models do not provide understanding of the effect of each training intensity on performance.

The objective of this study was to compare the predictive accuracy of these two normalisation approaches to others based on: a/ alternative normalisations, b/ summary scores derived from data, and c/ machine learning techniques, with recognised predictive qualities, such as Partial least squares or Lasso (Hastie et al. 2009). While alternative normalisations still leading to a single training variable,
summary scores allows for two or three training variables and machine learning are appropriate for dealing with a large number of training variables.

**Methods**

**Data**

Training volumes at eight intensity levels and performances in competition of 138 professional French swimmers were collected during 20 seasons, between 1991 and 2011. Log-performance times in competition were related to the top 10 world log-performances (of the same specialty, distance, sex and year). Training intensities were determined from lactate thresholds, using measurements of blood lactate concentrations, updated several times throughout the season (Mujika et al. 1996; Avalos et al. 2003). An incremental test to exhaustion was performed at the beginning of each season (repeated and adjusted four times per season) to determine the relationship between blood lactate concentration and swimming speed. Each subject swam 6x200-m at progressively higher percentages of their personal best competition time over this distance, until exhaustion. Lactate concentration was measured in blood samples collected from the fingertip during the 1-min recovery periods separating the 200-m swims. All swimming sessions were divided into five intensity levels according to the individual results obtained during this test: swimming speeds (1) below ~2 mmol.l⁻¹; (2) at ~4 mmol.l⁻¹, the onset of blood lactate accumulation; (3) just above ~6 mmol.l⁻¹; (4) at ~10 mmol.l⁻¹; and (5) at maximal swimming speed. In-water workouts were quantified in meters per week at each intensity level. Strength training included (6) dryland workouts of resistance training, (7) dryland workouts at maximal strength, and (8) general conditioning (involving cycling, running, cross-country skiing, team sports, etc.), and it was quantified in minutes of active exercise per week.

**Longitudinal data modelling and criteria for evaluating models performance**

This is an observational study with no control on training programs. We assumed that swimmers may react differently to the same training load (interindividual differences) and over time (intraindividual differences), thus we used mixed-effects models adjusted for sex, age, swim distance and specialty. Non-linear effects were tested using fractional polynomials (Sauerbrei et al. 2007).

The comparison criterion was the cross-validated prediction error to avoid for over-optimistic results about the quality of the modelling procedures (Hastie et al. 2009). Cross-validation consists of removing each subject from the analysis, re-fitting the model on remaining participants, and then testing the prediction on the excluded subject using the new model. The procedure is repeated for all subjects and prediction rates averaged across all iterations. Analyses were stratified by distance.

**Compared methods**

We adapted to our data the following methods: 1/the score proposed by Mujika et al. (1996), 2/the normalisation proposed by Avalos et al. (2003), 3/the normalisation ‘sum of training intensities expressed as a percentage of the common maximum’, 4/zero-mean and unit-variance individual normalisation, 5/zero-mean and unit-variance common normalisation, 6/a score for in-water and for dryland workouts based on univariate regressions, 7/a score for low-intensity and high-intensity in-water workouts, and for dryland workouts based on univariate regressions, 8/Partial least squares (PLS) regression and 9/the Lasso (least absolute shrinkage and selection operator) regression.

Scores based on regressions were computed by regressing one intensity training (used as unit reference) on the other intensity trainings (one by one) accounting for inter-subject variability and intra-subject data correlation. For example, in-water score was obtained as: Intensity 1 + β²₁ X Intensity 2 + β²₂ X Intensity 3 + β²₃ X Intensity 4 + β²₄ X Intensity 5, where coefficients were estimated from Intensity 1 = β₀ + β₁ X Intensity K + εᵢj, with i = 1,...,N the number of subjects; j=1,...,n the number of observation for the i-th subject and K=2,...,5 the in-water intensity levels. Low-intensity in-water score was computed from intensities 1 to 3, high-intensity in-water score was computed from intensities 4 to 5.
The underlying assumption of Partial Least Squares (PLS) is that the observed data is generated by a system or process which is driven by a reduced number of latent (not directly observed or measured) variables. PLS creates orthogonal components by maximising the covariance between sets of independent variables and the dependent variable. Then these components serve as a new representation of the set of independent variables and the dependent variable is regressed on these new predictors. We used R (R Development Core Team, 2011) version 2.13.1 for all computations. The R package `nlme` and `pls` were used to fit mixed models and PLS, respectively. We used a two-step procedure: first the PLS is fitted assuming independent data, second the PLS components are introduced in a mixed-effects model (Guyon et al. 2011).

Finally, the Lasso is a shrinkage method that can be applied to address estimate variance inflation or convergence problems, which arise in complex regression situations, such as in the presence of a large number of variables (Hastie et al. 2009). The Lasso maximises the likelihood function, with a bound on the sum of the absolute values of the coefficients, which ensures that unstable estimates are shrunk more than stable ones. As a result, the Lasso may completely delete certain covariates, those showing no association with the dependent variable, performing both estimation and variable selection simultaneously. The R packages `lmlasso` (Schelldorfer et al. 2011) and `glmmLasso` (Groll et al. 2011) were tested to compute the Lasso estimates for longitudinal data.

Results

Summary scores for three training loads (low-intensity/high-intensity/dry-land workouts) with data derived weights showed the best results. However, cross-validated prediction errors were close relative to their variances, which were high. Figure 1 shows mean prediction errors and standard deviation estimated through cross-validation for all the tested methods excepting the Lasso. For this last method, convergence problems appeared whatever the available algorithm used.

![Figure 1](image.png)

Note: 1,249, 1,455 and 254 weeks-person are used in sprint, mid- and long-distances analyses, respectively. Values are means±SD.

Discussion and conclusion

A possible explanation for the similar results and high variability achieved by different methods may be that several unmeasured variables contribute to performance. For example, no information is provided about the propelling efficiency, one of the most correlated factors with performance in swimming (Toussaint et al. 1992; Huang et al. 2010). Indeed, a good swimming technique depends on the ability to produce a high mechanical power output enabling the generation of high propulsive forces, besides the ability to reduce drag while, as well as, keeping power losses to pushed away water low (i.e. swimming with a high propulsive efficiency). For a similar training load, a swimmer trained with a bad technique will perform poorly than a swimmer trained with an efficient one. Another example, neuromuscular fatigue induced by intensive anaerobic could induce a decline in propulsive efficiency with a progressive increase in the energy cost (Toussaint et al. 1992; Zamparo et
However, the deterioration in stroking mechanics occurring as a consequence of local muscle fatigue has never been integrated in the training load computation. Busso et al. (2006) outlined the simplifications inherent to mathematical model approaches and questioned their relevance in predicting athletes’ responses to training.

Another possible explanation is that the lactate sensitivity to extraneous factors (mode of exercise, technique quality of training, diet or sleep quality prior to test) and the subject-specific variations in lactate thresholds introduce not negligible measurement error (Borresen et al. 2009). Also, similar concentrations at the blood level correspond to different mean anaerobic energy delivery at the cellular level (Olbrecht et al. 1985). In particular, for similar blood lactate concentrations (thus for similar training loads), the mean anaerobic energy delivery will be higher for short training and competition swimming distances, and for highest level swimmers with a good aerobic capacities. For instance, the anaerobic energy is twice higher when world class swimmers are compared to regional performers on the same swim distance and for the same blood lactate concentration. In that situation, errors-in-variables models might be more appropriated (Carroll et al. 2006).

Desgorces et al. (2007) proposed a training load measure integrating the cumulated work, endurance limit but also work and recovery durations. Compared to classical methods to quantify the training load (i.e. heart rate, blood lactate, rate of perceived exertion, delayed onset muscle soreness), this measure quantified a wide range of intermittent training sessions with lower variability and higher precision. Interestingly, the authors observed that the differences induced by exercise volumes (i.e., duration and number of repetitions) and by intensity units (minutes, seconds, and number of repetitions) were reduced when using this new training load measure. Others have also highlighted the weakness of indices such as heart rate and rate of perceived exertion in activities of intermittent nature or high intensity (Alexiou et al. 2008). Foster (1998) showed that the consideration of training monotony indices allowed improving significantly the prediction of the overtraining and illness compared with the only training load.

Integrative approaches quantifying training load from several widely used physiological indices (such as heart rate, blood lactate, rate of perceived exertion and delayed onset muscle soreness) might allow us advancing in this research area in the near future. As immediate practical recommendation, we suggest completing lactate (or other) measurements with athlete/coach questionnaires to better assess the physiological stress associated with the training load.

References


Relationship between body composition and competition performance in swimming

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Keywords: elite swimming, body composition, DXA

Introduction

In swimming, a multitude of physical, physiological, biomechanical and psychological parameters influence performance. While body composition is believed to be an important contributor to performance in swimming, with some coaches placing a strong emphasis on it during the training preparation phase, previous research is limited and inconclusive (Stager 1984; Siders et al. 1993; Carter & Ackland 1994; Anderson et al. 2008). Anthropometrical data of swimmers competing in the 1991 World Championships reported the best swimmers in all strokes were taller and had longer limb lengths (Carter & Ackland 1994). In that study the best performers in most strokes also had lower proportional skinfold thicknesses (Carter & Ackland 1994). In comparison to elite athletic groups in other sports such as running however, swimmers appear to have higher levels of body fat (Thorland et al. 1983). A study of adolescent female swimmers reported that while the faster swimmers had greater fat-free mass, there was no difference in body fat measurements compared with the slower swimmers (Stager et al. 1984). It has been previously suggested that a certain level of body fat may be useful for swimmers, enhancing buoyancy and body position in the water, or by providing rounded
Body surfaces which are more favourable for streamlining with less drag characteristics (Stager et al. 1984; Bixler 2005).

Body composition changes over the competitive season have been previously reported (Meleski & Malina 1985; Siders et al. 1993; Anderson et al. 2008). Siders et al. (1993) reported a decrease in fat mass and an increase in fat-free mass, along with a slight increase in body mass in female collegiate swimmers over a season; however, these changes in body fat were not associated with performance. In contrast, over a training season, an increase in lean mass in elite male swimmers and a reduction in skinfold in elite female swimmers has been demonstrated to correlate with enhanced swimming performance (Anderson et al. 2008). Since these studies the use of dual-energy X-ray absorptiometry (DXA) has become a common tool to comprehensively measure body composition in athletes. The purpose of this study was to evaluate the relationship between competition performance and body composition using DXA and other standard measurement practices in a group of elite swimmers.

Methods

The study sample consisted of twenty-six elite swimmers; 9 male (age 22.7 ± 2.7 y; mean ± SD) and 17 female (age 22.2 ± 2.8 y). All swimmers were, at a minimum, of national finalist standard with the cohort including Olympic and World Championship medalists. Over a 2 year period the body composition of the swimmers was measured in the weeks leading into, or following, the major long-course domestic competition (National Championships) and/or international competition (i.e. Olympic Games or World Championships) (19 ± 19 d before/after the competition; mean ± SD). A total of 59 performances with corresponding body composition measures were used in the investigation (2.3 ± 1.2 per swimmer). Performance times for each swimmer were recorded as the fastest swim in their best individual competitive event at each major competition. The swimmers’ performance times were then converted to a FINA point score (http://www.fina.org) in order to normalise the competition performance across the group.

Body composition measures of height, body mass, body mass index (BMI) and sum of 7 skinfolds (SF7) were recorded by an accredited anthropometrist in accordance with the recommended methods of the International Society for the Advancement of Kinanthropometry (Stewart et al. 2011). Dual energy x-ray absorptiometry (DXA) (Hologic Discovery W, Waltham MA, USA) was used to determine total lean mass (LM), total fat mass (FM), and % body fat (%BF). Measurements were made between 0600 and 0800 h with the swimmers presenting in a rested (no exercise prior) and overnight fasted state. All DXA scans were performed and analysed by the one trained technician and the positioning was standardised within the scanning area. The swimmers were instructed to present in a euhydrated state, and hydration status was determined from assessing the specific gravity of the first void urine sample using an automated refractometer (Pen-Urine S.G, Atago, Tokyo, Japan). Body mass was measured to the nearest 0.05 kg with digital standing scales (Model UC-321, A&D, Tokyo, Japan). Skinfold thickness was measured using calibrated Harpenden skinfold calipers (Baty International, West Sussex, UK). Measurements were taken from seven sites: triceps, subscapular, biceps, supraspinale, abdomen, front thigh, and medial calf. The anthropometrist’s typical error of measurement for the sum of seven skinfolds was 0.5 mm or 0.7%.

A subsection of 19 swimmers (8 male, 11 female) who underwent body composition assessments near the beginning of the season and near the main domestic competition (i.e. national championships) were analysed for the relationship between competition performance and the change in body composition measures over the domestic training preparation. A total of 26 performances with corresponding change in body composition measures over the domestic training preparation were evaluated (1.4 ± 0.5 per swimmer). Early season measures were performed 130 ± 37 d before the competition, while measurements towards the end of training preparation were collected 20 ± 9 d before the competition.

Data was analysed with SPSS (version 7.5, SPSS, Inc., Chicago, IL). Descriptive statistics (means ± SD) were calculated for all performance and body composition measures. Pearson correlations were
performed to determine the relationship between competition performance (FINA point score) and body composition measures. The subsection data evaluating the change in body composition measures from early to late in the season was converted to a percent change before correlations were performed. Paired t-tests were performed to analyse the change in body composition measures from early to late season. Magnitudes of all the correlations were interpreted using the following thresholds: 0.00-0.10 trivial, 0.10-0.30 small, 0.30-0.50 moderate, and >0.50 large (Cohen 1988). In all statistical analyses the 0.05 level of significance was adopted.

**Results**

Body composition data of the swimmers close to the major competition is shown in Table 1. The swimmers presented for body composition assessment in a moderately dehydrated state as determined by their urine specific gravity of 1.022 ± 0.01. For all swimmers combined there was a strong relationship between SF7 and DXA estimated fat mass (r = 0.84).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Descriptive data of competition performance and body composition variables measured near the main competition (mean 19 ± 19 d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All Swimmers n = 54</td>
</tr>
<tr>
<td></td>
<td>Male Swimmers n = 21</td>
</tr>
<tr>
<td></td>
<td>Female Swimmers n = 33</td>
</tr>
<tr>
<td>Performance—FINA Point Score</td>
<td>893 ± 44</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.80 ± 0.08</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>73.4 ± 10.1</td>
</tr>
<tr>
<td>Sum 7 Skinfolds (mm)</td>
<td>64.0 ± 23.0</td>
</tr>
<tr>
<td>Body Mass Index (kg.m⁻²)</td>
<td>22.5 ± 2.0</td>
</tr>
<tr>
<td>DXA Estimates:</td>
<td></td>
</tr>
<tr>
<td>Total Mass (kg)</td>
<td>72.5 ± 10.1</td>
</tr>
<tr>
<td>Lean Mass (kg)</td>
<td>55.5 ± 9.7</td>
</tr>
<tr>
<td>Fat Mass (kg)</td>
<td>14.4 ± 3.2</td>
</tr>
<tr>
<td>Percent Body Fat (%)</td>
<td>20.1 ± 4.7</td>
</tr>
</tbody>
</table>

Data are presented as mean ± SD

The relationship between competition performance and body mass, lean mass and fat mass for the male and female swimmers are shown in Figure 1. Overall, as a combined group there was only trivial to small relationships between the swimmers’ competition performance and the body composition measures (range: r = 0.17 to 0.00). The male swimmers had a large positive relationship between performance and body mass (r = 0.58; p = 0.006), fat mass (r = 0.58; p = 0.006), lean mass (r = 0.55; p = 0.01), height (r = 0.54; p = 0.01), and BMI (r = 0.50; p = 0.02). There was also a moderate positive relationship which trended towards significance for the male swimmers between performance and % body fat (r = 0.41; p = 0.06). While there was no statistically significant relationship between SF7 and competition performance for the male swimmers (r = 0.19; p = 0.42). Comparatively, for the female swimmers there was a large positive relationship between competition performance and height (r = 0.50; p = 0.01) and a moderate negative relationship approached significance between performance and % body fat (r = -0.32; p = 0.07). However, there was no statistically significant relationship between competition performance and body mass (r = 0.10; p = 0.59), lean mass (r = 0.28; p = 0.11), BMI (r = -0.24; p = 0.19), fat mass (r = -0.15; p = 0.39) and skinfolds (r = -0.16; p = 0.37) for the female swimmers.
The changes in body composition measures from early to late season are presented in Table 2. There were only trivial to small relationships between competition performance and the change in all body composition measures in both male and females over the training preparation ($r \leq 0.18; p > 0.05$). The relationship between competition performance and the percent change in SF7 from early to late in the training preparation is shown in Figure 2.
Table 2  Change in key body composition measures of the swimmers from early to late in the domestic training season

<table>
<thead>
<tr>
<th></th>
<th>Male Swimmers (n = 12)</th>
<th></th>
<th>Female Swimmers (n = 14)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Absolute Change</td>
<td>% Change</td>
<td>Absolute Change</td>
<td>% Change</td>
</tr>
<tr>
<td>Body Mass</td>
<td>-2.6 ± 1.4 kg*</td>
<td>-3.1 ± 1.6%</td>
<td>-0.8 ± 1.7 kg</td>
<td>-1.3 ± 2.7%</td>
</tr>
<tr>
<td>Sum 7 Skinfolds</td>
<td>-11.0 ± 5.5 mm*</td>
<td>-19.1 ± 9.1%</td>
<td>-8.0 ± 8.6 mm*</td>
<td>-10.1 ± 9.0%</td>
</tr>
<tr>
<td>DXA Estimates:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lean Mass</td>
<td>-0.9 ± 0.9 kg*</td>
<td>-1.3 ± 1.3%</td>
<td>0.2 ± 0.6 kg</td>
<td>0.5 ± 1.4%</td>
</tr>
<tr>
<td>Fat Mass</td>
<td>-1.7 ± 1.2 kg*</td>
<td>-11.8 ± 8.4%</td>
<td>-1.0 ± 1.4 kg*</td>
<td>-6.5 ± 8.7%</td>
</tr>
</tbody>
</table>

*Denotes a significant change (p < 0.5).

Data are presented as mean ± SD

Figure 2  Relationship between competition performance (FINA point score) and the change in skinfolds from early to late season for the male and female swimmers

Discussion

The present study characterised the body composition of elite swimmers leading into or just after the major competition of the season and the relationship to swimming performance at the major end-of-season competition. Strong positive relationships were observed between competition performance and body composition measures of body mass, fat mass and lean mass in the male swimmers in the present study. In contrast, the female swimmers had a moderate negative relationship between performance and percent body fat as estimated by the DXA, however no or only small relationships were observed between performance and all other body composition variables. Similar to previous research on the anthropometrical characteristics of swimmers (Thorland et al. 1983; Carter & Ackland 1994), there was a positive relationship between height and swimming performance for both the male and female swimmers.

Swimming training over a season is typically associated with increases in lean tissue and reductions in fat mass (Meleski & Malina 1985; Siders et al. 1993; Anderson et al. 2008). Previous research has demonstrated an increase in proportional lean mass in several phases of the season which is highly correlated with an improved end-of-season competition performance in male swimmers (Anderson et al. 2008). While in female swimmers, the major body composition changes of a decrease in body mass and body fat, with an increase in lean mass previously observed (Meleski & Malina 1985; Siders et al.
1993), primarily occurred in the early part of the season and were maintained during the second half of the preparation (Meleski & Malina 1985). From early in the training preparation to near the major competition of the season, mean changes in the present study of ~3% were observed for body mass in male and ~1% in female swimmers. This loss in body mass was primarily due to decreases in fat mass which was also observed in a decrease in SF7, with only small increases in lean mass. All of these changes only showed a small non-significant relationship with end-of-season competition performance.

In conclusion, body composition measures appeared to be more strongly related to competition performance for the male swimmers, where positive relationships were observed for body mass, fat mass and lean mass. While in the female swimmers other factors aside from body composition appear to account for a greater amount of the variation in performance.

References


Oxygen uptake kinetics and biomechanical behaviour at different percentages of VO2max

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Keywords: swimming, VO2kinetics, biomechanics, VO2max

Introduction

Sustaining exercise beyond a few seconds depends upon the appropriate supply and utilisation of oxygen (Jones and Poole 2005). However, the kinetics of oxygen uptake (VO2) response to exercise depends on its intensity, being described three main exercise intensities – moderate, heavy and severe (Gaesser and Poole 1996)—and more recently, a fourth much less studied one – extreme (Hill et al. 2002). The VO2 kinetics at moderate and heavy exercise intensities is well documented in the
literature, namely in treadmill running and cycle ergometer exercise (Sousa et al. 2011b; Burnley and Jones 2007). To date, the investigation of VO₂ kinetics in swimming has been limited either by the use of specific competitive distances (Rodríguez et al. 2003; Sousa et al. 2011b; Sousa et al. 2011a) or by presenting the VO₂ slow component as the only kinetic parameter of the VO₂ response (Demarie et al. 2001; Fernandes et al. 2003). The purpose of this study was to compare the VO₂ kinetics and biomechanical responses in three time to exhaustion exercises from rest to different percentages of maximal oxygen uptake (VO₂max) intensity – 95, 100 and 105%.

**Methods**

Five national male swimmers (16.6 ± 2.8 yrs, 68.1 ± 3.9 kg and 1.78 ± 0.05 m) volunteered to participate in the study. All were familiar with the testing procedures, as they were involved in previous swimming evaluations. The subjects were tested in four different occasions over a two weeks period, always at the same time of the day for each subject and separated by, at least, 24 h from other test.

In the first session, VO₂max and the minimum velocity correspondent to VO₂max (vVO₂max) were assessed through an incremental protocol performed in the front crawl technique, with 200 m steps duration and increments of 0.05 m.s⁻¹ and 30 s intervals until exhaustion between each step. The initial velocity was set at the swimmers’ individual performance on the 400 m freestyle minus seven increments of velocity, as described previously by our group in the Biomechanics and Medicine in Swimming Symposium in Ste. Etienne 2002 (Cardoso et al. 2003). VO₂max was considered to be reached according to primary and secondary criteria (Howley et al. 1995) and its mean value was measured over the last 60 sec of the exercise. In the following 3 sessions, time to exhaustion exercises were performed in randomised order until voluntary exhaustion: 95, 100 and 105% of VO₂max. Each test was preceded by 10 min warm up at 60% of VO₂max followed by a short rest period. Then, each swimmer was asked to maintain the defined vVO₂max intensity until exhaustion. In all sessions, velocity was controlled by a visual pacer with flashing lights in the bottom of the pool (TAR.1.1, GBK-electronics, Aveiro, Portugal), and the tests ended when the subjects could no longer maintain the required velocity.

Gas-exchange parameters were directly measured using a telemetric portable gas analyzer (K4b², Cosmed, Rome, Italy), connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system (Baldari et al. 2012). In-water starts and open turns, without underwater gliding, were used. After including only the VO₂ values in-between VO₂mean ± 4 standard deviation, individual breath-by-breath VO₂ responses were smoothed (3-breath moving average) and time-averaged in 5-s. To allow the comparison of the VO₂ kinetic responses, data was modeled using a double exponential model—$$\text{VO}_2(t) = A_0 + A_1 \exp (-\frac{t}{\tau_1}) + A_2 \exp (-\frac{t}{\tau_2})$$—with a nonlinear least squares method implemented for baseline VO₂ ($A_0$), amplitudes ($A_1$ and $A_2$), time delays ($TD_1$ and $TD_2$) and time constants ($\tau_1$ and $\tau_2$) assessment (representing the VO₂ kinetics fast -1- and slow -2-components). Stroke rate (SR) was determined as the number of strokes per min (registered by the number of strokes in each 25 m), stroke length (SL) was calculated by dividing velocity by SR, and the product of SL to velocity allowed the assessment of stroke index (SI). Comparison between conditions was performed using ANOVA repeated measures with Bonferroni post-hoc test with the level of significance set at $p<0.05$. Since a limited sample was used, effect size was computed with Cohen’s f. It was considered (1) small effect size if $0 \leq |f| \leq 0.10$; (2) medium effect size if $0.10 < |f| \leq 0.25$; and (3) large effect size if $|f| > 0.25$ (Cohen 1988).

**Results**

Table 1 shows the mean ± SD values for the VO₂ kinetics and biomechanical parameters obtained in all square wave transitions.
Mean ± SD values for the VO₂ kinetics and biomechanical parameters obtained at 95, 100 and 105% of vVO₂max intensity. 1,2,3 Different from 95, 100 and 105% conditions, respectively (p<0.05).

<table>
<thead>
<tr>
<th>Exercise Intensity</th>
<th>A₀</th>
<th>A₁</th>
<th>TD₁</th>
<th>τ₁</th>
<th>A₂</th>
<th>TD₂</th>
<th>τ₂</th>
<th>SF</th>
<th>SL</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%</td>
<td>17.5±2.4</td>
<td>37.4±5.2</td>
<td>9.1±3.7</td>
<td>16.1±2.1</td>
<td>4.3±1.8</td>
<td>120.5±36.7</td>
<td>87.8±22.7</td>
<td>0.59±0.01</td>
<td>2.29±0.2</td>
<td>3.08±0.3</td>
</tr>
<tr>
<td>100%</td>
<td>18.2±2.4</td>
<td>35.7±3.1</td>
<td>7.4±2.3</td>
<td>17.4±3.6</td>
<td>7.4±1.9</td>
<td>76.9±24.4</td>
<td>63.1±13.1</td>
<td>0.63±0.01</td>
<td>2.24±0.2</td>
<td>3.16±0.3</td>
</tr>
<tr>
<td>105%</td>
<td>18.9±3.9</td>
<td>36.7±5.6</td>
<td>9.1±4.6</td>
<td>19.8±11.4</td>
<td>2.6±1.5</td>
<td>72.5±18.8</td>
<td>72.6±5.6</td>
<td>0.66±0.01</td>
<td>2.25±0.2</td>
<td>3.34±0.3</td>
</tr>
</tbody>
</table>

A₀ = baseline VO₂; A₁, TD₁ and τ₁ = fast component amplitude, time delay and time constant, respectively; A₂, TD₂ and τ₂ = slow component amplitude, time delay and time constant, respectively; SF = stroke frequency; SL = stroke length; SI = stroke index.

There were no differences for the kinetic parameters between trials, with the exception of A₂ between 100% and 105% of VO₂max (Table 1). Regarding the biomechanical parameters, SF and SI increased with increasing velocity. However, SF was significant different between 95% and the other conditions and SI was higher in 105% intensity compared to the other two conditions. The intensity at which each square wave transition was performed (95, 100 and 105% of vVO₂max) had a large effect on A₂ (F(32.55; 5.18) = 6.27, P < 0.02, f = 0.61), SF (F(0.008; 0.000) = 41.84, P < 0.000, f = 0.91) and SI values obtained (F(0.11; 0.004) = 28.11, P < 0.001, f = 0.87).

An individual VO₂ kinetic response, the corresponding mean values of the time sustained at each studied intensities and the relationships obtained between the kinetic and biomechanical parameters are shown in Figure 1.

The time sustained was higher at 95% compared to 100% and 105% intensities, and lower at 105% compared to 100% vVO₂max swimming intensity. Inverse relationships were obtained between τ₁ and SL and between τ₂ and SI in the 95% vVO₂max exercise intensity. No significant correlations were observed in the 100 and 105% exercise conditions.

Discussion

The analysis of the VO₂ kinetic response across different percentages of VO₂max intensities has never before been conducted in swimming. That aerobic power is one of the main physiological requirements of swimming also evidences the pertinence of its study. Its purpose was to compare the VO₂ kinetics and biomechanical responses at different percentages of VO₂max intensity – 95, 100 and 105%. These intensities were not sufficient to promote changes in both fast and slow components, with the exception of A₂. However, the different intensities were responsible for an increase in SF and SI, without changing SL.
The mean values of $A_1$ obtained are in accordance with previous studies conducted at swimming heavy intensity (Reis et al. 2010; Reis et al. 2011), but are lower than those presented for the extreme domain (Sousa et al. 2011b; Sousa et al. 2011a). During the fast $\text{VO}_2$ component, the increase in amplitude is described to be related with the increase in exercise intensity (Pringle et al. 2003; Scheuermann and Barstow 2003). However, in the present study no differences were found between the 95, 100 and 105% of $\text{VO}_2\text{max}$ intensities. Regarding $\tau_1$, the present values corroborated the specialised literature (Reis et al. 2010; Reis et al. 2011) but are lower than those obtained for all-out swimming (Sousa et al. 2011b; Sousa et al. 2011a; Rodríguez et al. 2003) and cycling exercises (Scheuermann and Barstow 2003). There is little consensus regarding whether or not the $\tau_1$ remains constant or modifies as exercise intensity increases (Jones and Poole 2005), however no differences were found between the distinct intensities. The mean $A_2$ values reported at 100% $\text{VO}_2\text{max}$ were higher than those suggested previously for the same swimming intensity (Fernandes et al. 2003; Fernandes et al. 2008), but in accordance with those reported for lower intensity domains (Reis et al. 2010; Reis et al. 2011). In addition, $A_2$ was higher in the 100% $\text{VO}_2\text{max}$ compared to 105% $\text{VO}_2\text{max}$ condition. In fact, at the severe domain the $\text{VO}_2$ slow component is much more developed comparing to the extreme domain, (Xu and Rhodes 1999). Moreover, in the 95% $\text{vVO}_2\text{max}$ intensity the subjects showed also a $\text{VO}_2$ slow component phenomenon with physiological meaning (< 200ml.min⁻¹), a fact not observed at the highest intensity studied (105% $\text{vVO}_2\text{max}$). In fact, this latter intensity as being part of the extreme intensity domain, the $\text{VO}_2$ slow component did not occur as it was previously reported during cycling exercise at 110% $\text{VO}_2\text{max}$ intensity (Scheuermann and Barstow 2003).

The time sustained at 95% $\text{vVO}_2\text{max}$ was higher compared to 100 and 105% $\text{vVO}_2\text{max}$ with a progressive increase of the SR and SI as intensity increased. The opposite trend was observed for SL, although without statistical significance. The increase in SR compensated the reduction in SL, which corroborates previous swimming observations (Alberty et al. 2008; Alberty et al. 2009). In fact, the swimmers of the current study showed a mechanic adaptation at higher velocities by increasing SR, with a concomitant tendency to decrease the SL, which contributed to higher SI values in 105% $\text{vVO}_2\text{max}$ compared to the 100% intensity condition. Moreover, inverse correlations were found between $\tau_1$ and SL, and SI at 95% $\text{vVO}_2\text{max}$ swimming intensity, suggesting that swimmers with a higher SR and SI experienced more difficulties in achieving $\text{VO}_2$ steady state phase at this exercise intensity. Hence, the capacity to maintain high rates of SL and SI at 95% $\text{vVO}_2\text{max}$ seems to indicate an improvement in the $\text{VO}_2$ kinetic response, being technical efficiency an important factor at this swimming intensity.

**Conclusions**

The present results showed that the different exercise intensities performed were not sufficient to promote significant changes in both fast and slow components, with the exception of $A_2$. However, the different intensities were sufficient to promote an increase in SR and SI, which reflects the mechanic adaptation of the swimmers at higher velocities.

**Acknowledgments**

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Changes in urine volume and subjective micturition during a sitting posture while in water

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Keywords: urine volume, subjective micturition, in water, rectal temperature, venous return

Abstract
In this study we investigated the relationships between urine volume, subjective micturition, reported thermal sensation, heart rate (HR), skin temperature, blood pressure, and rectal temperature during a sitting posture while in water. Eleven healthy males volunteered for this study. This study included two experimental conditions: a land condition (L) and a water condition (W). During the L condition, a subject assumed a sitting position on land for 120 minutes. Both conditions began with 30 minutes in a sitting posture on land. Then, for the next 30 minutes, a subject sat in water for the W condition, whereas a subject sat on land for the L condition. Finally, for the last 60 minutes, both conditions had the subject back on land in a sitting posture. Urine volume, subjective micturition and skin temperature after immersion in water, recovery at 30 minutes and recovery at 60 minutes in the W was higher than that of L (p < 0.05). Reported thermal sensation in water, between recovery at 5 minutes and recovery at 15 minutes in the W was higher than that of L (p < 0.05). HR in water, recovery at 10 minutes and recovery at 15 minutes in the W was lower than that of L (p < 0.05). Rectal temperature in water at 30 minutes and recovery at 10 minutes in the W was lower than that of L (p < 0.05). Blood pressure in water and recovery in the W was lower than that of L (p < 0.05). While in water, venous return in the body increases due to water pressure, which increases urine volume. Urine volume and subjective micturition increase due to immersion in water.

Introduction
Previous studies have demonstrated that physiological responses while in water differ from those while on land due to the physical characteristics of water [7]. Venous return and urine formation increases while in water, after which a diuretic effect increases [3,4]. Compared with land exercise, the loss of body fluid in water exercise increases due to urine [6]. While in water, kidney blood flow and a condition Na diuretic hormone levels increase [2,10]. A decrease in plasma renin activity and aldosterone levels cause this increase in urine volume [2,10].

Kasugai et al. compared these measures between males who were swimming club members and males who did not having a habit of swimming [5]. They found that in both groups, urine volume had a tendency to increase, which reflected a diuretic effect. Based on these results, we assumed that an increased diuretic effect while in water was caused by two factors due to physiological effects while in water. Thus, the purpose of this study was to investigate the relationships between urine volume, subjective micturition, reported thermal sensation, HR, skin temperature, blood pressure, and rectal temperature while in a sitting posture in water.

Methods
Measurement conditions
This study included two experimental conditions: a land condition (L) and a water condition (W). The water level was set to the level of a study subject’s clavicle.

Subjects and environmental conditions
We recruited eleven healthy male Japanese volunteers for this study. Their mean age was 21.3 ± 0.9 years, mean height was 167.8 ± 4.5 cm, mean body weight was 69.1 ± 6.5 kg, and mean body fat percentage was 14.3 ± 3.3%. The environmental conditions in a swimming pool area were as follows:
Written informed consent was obtained from all subjects before their enrolment in this study. This study was approved by the Ethics Committee of the Faculty of Health Science and Technology of Kawasaki University of Medical Welfare (Japan). Our study protocol was in accordance with the Declaration of Helsinki. None of the subjects smoked or had medical histories, including metabolic diseases, which may have affected the cardiovascular system. The subjects were instructed to refrain from consuming caffeine and alcohol and performing high-intensity exercises for two days before the experiment to control for withdrawal or the acute effects of these drugs and exercise on our primary outcome measures.

Protocol
Under the L condition, a subject assumed a sitting position on land for a total of 120 minutes. Both conditions began with 30 minutes in a sitting posture on land. Then, for the next 30 minutes, a subject sat in water under the W condition, while a subject sat on land under the L condition. Finally, for the last 60 minutes for both conditions, a subject was back on land in a sitting posture.

Each subject participated in both conditions. For each condition, the measurements were made on different days at the same time in the morning. Subjects were instructed to have no alcoholic drinks the day before the measurements were made and to have no meals and no caffeine drinks after 10:00 PM on the day before the measurements were made.

Measured items
Urine was collected and the volume measured after urination every 30 minutes. Subjective micturition was measured using Visual Analog Scale [11] (VAS) every 30 minutes. Skin temperature was measured using a skin temperature monitor (NIKKISO-THERM CO., LTD. Japan) every 30 minutes. The evaluation of reported thermal sensation used the thermal sensation method of Tanaka, et al. [10]. Reported thermal sensation was measured at rest every 5 minutes after the water level reached the clavicle. In the water, HR was measured every 5 minutes using a HR monitor (RS400; POLAR, Sweden). Rectal temperature was measured using a rectal temperature monitor (YSI4000, NIKKISO, Japan) from the time of resting and the start of the measurements every 10 minutes. Blood pressure (SBP: Systolic Blood Pressure/DBP: Diastolic Blood Pressure) (501; KENZMEDICO, Japan) was measured from the time of resting and the start of the measurements every 10 minutes.

Statistical analysis
Results for HR, rectal temperature, skin temperature, blood pressure, and urine volume are given as means ± standard deviations. Results for subjective micturition and reported thermal sensation are given as median values. HR, rectal temperature, skin temperature, blood pressure, and urine volume results were compared using two-way ANOVA. A Wilcoxon signed-rank test was used to compare subjective micturition and reported thermal sensation results between the measurement points. Statistical significance was set at <0.05. Statistical analyses used SPSS ver. 12.0 for Windows.

Results
Urine volume (Fig. 1), subjective micturition results (Fig. 2) after immersion in water, and recovery at 30 minutes and 60 minutes were higher under the W condition than under the L condition (p < 0.05). Reported thermal sensations while in water, between recovery at 5 minutes and 15 minutes, were higher under the W condition than under the L condition (p < 0.05). Subjects reported the water temperature as too cold. HRs (Figs. 3, 4) while in water and recovery at 10 minutes and 15 minutes were lower under the W condition than under the L condition (p < 0.05). Rectal temperature (Fig. 5) while in water at 30 minutes and recovery at 10 minutes were lower under the W condition than under the L condition (p < 0.05). Blood pressure while in water and recovery were lower under the W condition than under the L condition (p < 0.05). Skin temperatures after immersion in water and...
recovery at 30 minutes and 60 minutes were higher under the W condition than under the L condition (p < 0.05).

* Figure 1  Comparison of urine volume between W and C conditions

* Figure 2  Comparison of subjective micturition results between W and C conditions

* p < 0.05, W condition vs. L condition.
Urine volume, subjective micturition results after immersion in water, and recovery at 30 minutes and 60 minutes were higher under the W condition than under the L condition. Blood pressure also increased. We have reported elsewhere [7] that water immersion inhibits the secretion of antidiuretic hormone reducing the reabsorption of water by the kidney increasing urine volume.

While in water, venous return in the body increases due to the water pressure, and the stroke volume and HR are decreased [7]. Venous return increases due to the water level [7]. The stroke volume significantly increases when the water level reaches the level of the xiphoid process [7]. HRs while in water resting conditions were lower as than those on land resting conditions, a result which was in agreement with a previous report.

After movement, the blood volume increases and causes changes in the concentrations of various hormones. Permeation pressure is at 100% before entering the water, and is reduced by 20% for 30 minutes in water [7]. Permeation pressure increases and antidiuretic hormone secretion increases [5]. These affect the kidney and help in conserving water. By comparison, an increased water level decreases the water pressure, resulting in a decrease in the antidiuretic hormone secretion, which in turn results in water diuresis and water discharge [6]. For 30 minutes, an increase in blood volume increases the urine volume and subjective micturition. Subjective micturition, reported thermal sensation, rectal temperature, skin temperature, and urine volume were significantly increased.

**Discussion**

*Figures 3, 4  Comparison of HRs between W and C conditions*

*Figures 5  Comparison of rectal temperatures between W and C conditions*
during water resting conditions compared with those during land resting conditions. This phenomenon with urine occurs while in water [3,4].

The thermal conductivity of water is approximately 25 times higher than that of air [7]. The water temperature in a swimming pool in Japan during water exercises is in the range of 30–31°C [7]. In this range of water temperature, the rectal temperature is lower because the thermal conductivity of water is high [7]. We previously reported that water temperature had an effect on temperature changes in humans within a short time [8].

Therefore, an increase in urine volume while in water can lead to an increase in subjective micturition. The body temperature falls, and radiation due to vasoconstriction is lower due to the thermoregulatory center in the hypothalamus. The blood in the central part increases to maintain temperature.

**Conclusions**

1. Urine volume and subjective micturition increase due to immersion in water.
2. Urine volume progressively decreases during the recovery time.

**References**

**VO₂ assessed by backward extrapolation in 200, 400, 800, and 1500 m front crawl in youth swimmers**

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**Keywords:** swimming, oxygen consumption, training and testing

**Abstract**

The aim of this study was to compare oxygen consumption (VO₂) responses assessed by backward extrapolation after 200, 400, 800 and 1500 m in youth swimmers. VO₂ in the 400 m was greater than all other distances, with enough time and intensity for the swimmers to achieve VO₂max at the end of the 400 m maximal effort. Although less accurate and precise, backward extrapolation technique was confirmed to be attractive and able to identify similar VO₂ values to those obtained during swimming with direct assessment methods.

**Introduction**

Swimming is a mainly aerobic sport in which the anaerobic system contribution has significant influence (Capelli et al. 1998; Gastin 2001; Figueiredo et al. 2011). In this sense, maximal oxygen consumption (VO₂max) can be considered the expression of maximal metabolic aerobic performance capability (aerobic power) of a subject and, therefore, is related to primary areas of interest in swimming: training and performance diagnostic (Olbrecht 2000; Libicz et al. 2005; Sousa et al. 2011).

VO₂max assessment in swimming is always a great challenge (Pelayo et al. 2007). Although direct assessments are reliable to measure VO₂max (Toussaint et al. 1987, Keskinen et al. 2003; Baldari et al. 2013), ecology in some swimming strokes seems to be impaired: a) side breathing is not possible; b) mostly the turns are not performed, and c) some changes can occur in hydrodynamics (Montpetit et al. 1981; Keskinen et al. 2003; Barbosa et al. 2010). In an attempt to minimise this problem, an ecological alternative has been used for some years: the backward extrapolation of the VO₂ recovery curve (Di Prampero et al. 1976; Léger et al. 1980).

Backward extrapolation was first tested in swimmers by Lavoie et al. (1983), where VO₂ was assessed immediately after swimming, and a regression curve between time and VO₂ values were applied to predict VO₂ in time zero (Lavoie & Montpetit 1986). Peak VO₂ values measured during the first 20 s of recovery of a 400 m front crawl maximal effort were not significantly different than the VO₂ obtained with the Douglas bag method during the same event (Lavoie et al.1983). Costill et al. (1985) also verified that it is possible to accurately determine VO₂ during maximal and submaximal swimming using expired gas collection taken immediately after a 4-7 min swim.

Since Lavoie et al. (1983), the 400 m maximal effort in front crawl is a reference to verify maximal aerobic speed (aerobic power) and to prescribe swimming training intensities (Rodriguez 2000; Pelayo et al. 2007). At 400 m maximal effort, swimmers are able to maintain a swimming speed corresponding to the minimum speed required to obtain VO₂max (Fernandes & Vilas-Boas 2006, 2012). Although backward extrapolation seems not to be as reliable as other techniques, its use attempts to answer many coaches who seek to respect the ecology of the stroke analyzed. Thus, this study aimed to compare VO₂ responses obtained by backward extrapolation technique at distances of 200, 400, 800 and 1500 m in front crawl.
**Methods**

**Participants**

Twelve (eight males and four females) front crawl swimmers (15.6 ± 0.9 years old, 63.0 ± 7.2 kg body mass, 174.9 ± 8.3 cm height, and 180.7 ± 10.4 cm arm span and 280.2 ± 18.0 s = 79.0 ± 3.3% of the 25 m pool World Record over a 400 m freestyle event) volunteered to this study. All swimmers had at least 6 years of experience as competitive swimmers, and were training without interruptions before and during the data collections. The protocol was approved by the University ethics committee and it was explained to the swimmers, who gave their written consent to participate, which was signed by a legal guardian since the participants were under 18 years old.

**Swim trials**

The protocol involved the performance of 200, 400, 800, and 1500 m all-out effort (randomised and 24h interval in between). All trials were performed in front crawl with a push start (25-m outdoor pool; ≈29°C and ≈31.5°C, respectively for water and air temperature). VO$_2$, blood lactate concentration [La], perceived exertion (PE) and heart rate (HR) were measured immediately after each distance. All times were recorded at the nearest 0.01 s by two qualified timekeepers.

**Metabolic parameters**

VO$_2$ was measured using the portable gas Analyzer VO2000® (Medgraphics, Saint Paul, Minnesota – USA). The VO2000® apparatus was calibrated following the procedures described in specialised studies (Wahrlich et al. 2006; Oslon et al. 2008) before each assessment using known gas concentrations (SDTP) with a mini drum of 1.000 m$^3$. Expired gas concentrations were measured by the method of average breathing rate of three respiratory cycles. A Mouthpiece (Wahrlich et al. 2006) and a nose clip were applied to the face of the swimmer while staying with the water up to their shoulders. A dead space of 10 s was established, i.e., it was assumed that excluding the first ten seconds to calculate the values of VO$_2$ was enough to ensure that the system evaluated only the gases exhaled by the swimmer. The adjustment of the VO2000® mouthpiece in the swimmers’ face lasted no more than 2 s after the end of each event. VO$_2$ assessed immediately after each all-out effort were measured for 1 min 50 s after the elimination of dead space. A linear regression curve between the time (20 s immediately after the 10 s of dead space) and VO$_2$ values was plotted into predict VO$_2$ when the time was zero (backward extrapolation).

Capillary blood samples (≈25 µl) for [La] analysis were collected from the fingertip of the hand during the recovery period (1, 3, 5 and 7 min after each all-out effort, [La]peak), using Accutrend Plus (Roche®). HR values (immediately after each all-out effort) were collected from the region of the xiphoid process (Polar Electro® S-610, Finland). The strap transmitter was already engaged before each event.

PE values (6-20 points, Borg 1982) after each all-out effort were also reported. VO$_{2max}$ was considered to be reached according to secondary physiological criteria (Howley et al. 1995): a) [La] level (≥ 8mmol·l$^{-1}$); b) High respiratory exchange ratio (r ≥ 1.0); c) High HR (≥ 90% of [220-age]); and d) High value of PE (visually controlled).

**Statistical analysis**

For all data, Shapiro-Wilk’s test (normality test) was applied. Since normality was confirmed, mean and standard-deviation were calculated. Data sphericity was verified with Mauchly test. Repeated-measures ANOVA were applied. Main effects were verified with Bonferroni post-hoc test. When necessary, Greenhouse-Geisser Epsilon correction factor was applied in the degrees of freedom. Eta$^2$ was applied as effect size indicator. Alpha was established in 5% and all the procedures were calculated in SPSS, v. 17.0.

**Results**

Values and standard deviations of time and VO$_2$ from 200-1500 m are presented in Table 1.
Table 1  Mean and standard deviations values of time and VO₂ from 200-1500 m maximal efforts, *p ≤ 0.001 found for comparison of VO₂ values between 400 m and all others events

<table>
<thead>
<tr>
<th></th>
<th>200 m</th>
<th>400 m</th>
<th>800 m</th>
<th>1500 m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time (s)</strong></td>
<td>132.1 ± 8.4</td>
<td>280.2 ± 17.6</td>
<td>578.9 ± 36.0</td>
<td>1126.0 ± 67.7</td>
</tr>
<tr>
<td><strong>VO₂ (ml·kg⁻¹·min⁻¹)</strong></td>
<td>47.4 ± 8.4</td>
<td>63.5 ± 8.7 *</td>
<td>51.0 ± 7.8</td>
<td>48.9 ± 4.8</td>
</tr>
</tbody>
</table>

VO₂ of 400 m was greater than all other distances (200m: p < 0.001; 800m: p = 0.001; and 1500 m: p = 0.001; \( \eta^2 = 0.697; \) power = 1.0) and showed high respiratory exchange ratio (1.24 ± 0.16; min: 1.03 – max: 1.43). The eta² result suggests that the event distance is responsible for ≈70% of the variance in VO₂.

\[ [\text{La}]_{\text{peak}} \] in 200, 400, 800 and 1500 m were 11.9 ± 1.7, 10.8 ± 2.0, 9.6 ± 1.6 and 9.1 ± 1.6 respectively. \([\text{La}]_{\text{peak}} \) from 200 were higher than 800 (p = 0.020) and 1500 m (p < 0.001). HR in 200 (176.5 ± 10.8 bpm), 400 (185.2 ± 13.6 bpm, 94.8 ± 5.7% HR_{\text{max}}), 800 (183.3 ± 18.6 bpm) and 1500 m (185.3 ± 9.1 bpm) were similar. PE values for 200, 400, 800 and 1500 m were 17.9 ± 1.6, 18.1 ± 1.5, 17.8 ± 1.9 and 18.2 ± 1.6 points respectively.

**Discussion**

The aim of this study was to compare VO₂ responses assessed by backward extrapolation at 200, 400, 800 and 1500 m. Time of 400 m in front crawl ranged from 257 to 311 s, and was similar to others studies for high level swimmers (Fernandes & Vilas-Boas 2006, 2012). VO₂ values recorded were consistent with those observed previously for swimmers (Chart 1).

Chart 1  Mean and SD of the higher VO₂ observed for maximum efforts of 200, 400, 800 and 1500 m

<table>
<thead>
<tr>
<th>Study</th>
<th>N</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Methodology</th>
<th>Equipment</th>
<th>VO₂ (ml·kg⁻¹·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Sousa et al.</em> (2011)</td>
<td>10</td>
<td>♂</td>
<td>21.6 ± 2.4</td>
<td>Breath by Breath Snekkel utilized during swimming</td>
<td>K4b2 (Connect, Italy)</td>
<td>68.58 ± 5.79</td>
</tr>
<tr>
<td><em>Dekerle et al.</em> (2010)</td>
<td>9</td>
<td>♂</td>
<td>21.2 ± 2.6</td>
<td>Maximum value during the first 20 s post test</td>
<td>K4b2 (Connect, Italy)</td>
<td>51.3 ± 6.8</td>
</tr>
<tr>
<td><em>Beidaris et al.</em> (2010)</td>
<td>12</td>
<td>♂</td>
<td>14-17</td>
<td>Backward extrapolation</td>
<td>VO2000® (Metaplan, USA)</td>
<td>45.4 ± 15.1</td>
</tr>
<tr>
<td><em>Platanou &amp; Geladas</em> (2006)</td>
<td>15</td>
<td>♂</td>
<td>22.4 ± 3.3</td>
<td>Backward extrapolation</td>
<td>Not specified</td>
<td>-</td>
</tr>
<tr>
<td><em>Laffite et al.</em> (2004)</td>
<td>15</td>
<td>♂</td>
<td>22.6 ± 3.6</td>
<td>Backward extrapolation</td>
<td>K4b2 (Connect, Italy)</td>
<td>-</td>
</tr>
<tr>
<td><em>Rodriguez et al.</em> (2002)</td>
<td>10</td>
<td>♂</td>
<td>19.1 ± 1.8</td>
<td>Post test value assessed on the sixth second after checking the VO₂ peak</td>
<td>K4b2 (Connect, Italy)</td>
<td>-</td>
</tr>
<tr>
<td><em>Wakayoshi et al.</em> (1993)</td>
<td>8</td>
<td>♂</td>
<td>19.4 ± 0.3</td>
<td>Prediction equation proposed by Costil et al., (1985)</td>
<td>Douglas Bags</td>
<td>-</td>
</tr>
<tr>
<td><em>Ribeiro et al.</em> (1990)</td>
<td>15</td>
<td>♂</td>
<td>16 ± 2</td>
<td>Backward extrapolation</td>
<td>Douglas Bags</td>
<td>-</td>
</tr>
</tbody>
</table>

Some studies suggest that VO₂ from 400 m in front crawl is very well correlated to the VO₂_{\text{max}} (Montpetit et al. 1981; Lavoie et al. 1983; Rodriguez 2000; Pelayo et al. 2007). In fact, VO₂ from 400 m
was the highest among the values related to the distances measured in the present study. The choice of backward extrapolation technique to obtain VO\(_2\) occurred by the interest in making the test environment the most real as possible, i.e., without changing the mechanics of swimming, allowing the swimmer to perform each distance identically to a competition situation (Montpetit et al. 1981; Keskinen et al. 2003; Laffitte et al. 2004; Barbosa et al. 2010).

Furthermore, the high respiratory exchange ratio reported \((r \geq 1.0)\) also meets the requirements to consider VO\(_{2\max}\) reached (Howley et al. 1995). \([\text{La}]_{\text{peak}}\) values were in agreement with those reported by others studies (Avlonitou 1996; Schnitzler et al. 2008; Vescovi et al. 2011; Sousa et al. 2011). \([\text{La}]_{\text{peak}}\) at 400 m \((10.7 \pm 2.03\text{ mmol} \cdot \text{l}^{-1})\) was consistent with that suggested by Howley et al. 1995 \((\geq 8 \text{ mmol} \cdot \text{l}^{-1})\) to consider VO\(_{2\max}\) achieved. Moreover, the \%HR\(_{\text{max}}\) required of \(\geq 90\%\) HR\(_{\text{max}}\) (Howley et al. 1995) was reached \((94.8 \pm 5.7\%\) HR\(_{\text{max}}\)) in this study. PE is understood as a complex representation, central and integrated of various bodily functions altered acutely by muscle activity and experiences with exercise (Borg 1982; ST Clair Gibson et al. 2003). The mean of \(18.1 \pm 1.5\) points achieved for PE in the 400 m consolidated all four physiological criteria (Howley et al. 1995) used in this study to assume that there was enough time and intensity to the swimmers achieve their VO\(_{2\max}\) at the end of 400 m maximal effort (Lavoie et al. 1983; Montpetit et al. 1981; Lavoie et al. 1983; Rodrigues 2000; Pelayo et al. 2007; Fernandes & Vilas-Boas 2006, 2012).

**Conclusion**

Youth swimmers have achieved VO\(_{2\max}\) at the end of the 400 m in front crawl. Although less accurate and precise, backward extrapolation technique confirmed to be attractive and able to identify similar VO\(_2\) values to those obtained during swimming with direct assessment methods.

**Acknowledgment**

The authors would like to thank, Rodrigo Carlet, Jessy Lauer, INBRASPORT (www.inbrasport.com.br), swimmers and Coaches Mirco Cevales and Christiano Klaser for the relevant support. Rodrigo Zacca acknowledges Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—CAPES (Brasil) for the MSc Grant.

**References**


Lactate peak in youth swimmers: quantity and time interval for measurement after 50–1500 maximal efforts in front crawl

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¹Universidade Federal do Rio Grande do Sul (UFRGS), Brazil, ²Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brazil

Keywords: exercise physiology, swimming, training and testing

The aim of this study was to compare lactate peak and area under the curve lactate-time (AUC) values at 50, 100, 200, 400, 800 and 1500 m maximal efforts in youth swimmers performing front crawl. Twelve (eight males and four females) youth swimmers (15.6 ± 0.9 years old, 63.0 ± 7.2 kg body mass, 1.75 ± 0.08 m height, and 1.81 ± 0.1 m arm span) volunteered to participate in this study. The protocol involved the performance in a randomised order of 50, 100, 200, 400, 800, and 1500 m all-out effort (24h interval). Capillary blood samples (±25 μl) for blood lactate concentration ([La]) analysis were collected after 10 min rest (Rest), after warm-up (Pre) and during the recovery period (1, 3, 5 and 7 min, [La]peak) after each event (50–1500 m) using Accutrend Plus (Roche®). AUC of [La] was calculated by the trapezoidal mathematical method, i.e., the sum of trapezoid areas AUC of [La] was expressed as percentage difference between each distance, with 50 being 100%. The highest [La] observed in 100 and 200 m indicates the high glycolitic contribution between 50–1500 events.

Factorial ANOVA found no difference between [La]peak of 100 and 200 m, but AUC showed difference of + 3% between 100 and 200 m. Area under the curve (AUC) of [La] may be applied in swimming.

Introduction

Blood lactate concentration ([La]) is widely used in swimming training intensity monitoring and reflect the balance between its production and catabolism (Joulia et al. 2003). It is also used to determine the energetic profile (Zamparo et al. 2011). Repeated blood samples within a short time interval, are essential for analyzing the dynamic behavior of this physiological measure (Beneke et al. 2005). However this process is not feasible due to the high cost of repeated tests and the high number of invasive samples that are taken. Usually, blood samples are collected 2 to 4 times at different time intervals to identify [La] peak (Chart 1).

However, sometimes, [La] values are so similar that statistical procedures are not able to identify differences when swim distances are compared (Bonifazi et al. 1993, Vescovi et al. 2011). An alternative to comparing [La] values is to calculate the area under the curve (AUC) for a plot of [La] and time. AUC is frequently used in clinical pharmacology to estimate the area inscribed by the plot of...
plasma, serum or whole blood drug levels versus time and can be interpreted as the total uptake or extent of exposure to a drug (Allison et al. 1995; Dello Strologo et al. 1999). This methodology also allows the identification of the persistence of an increase in [La], and to check the removal rate with higher values. AUC allows comparison of [La] values in each event as a percentage. This method allows a clearer and more precise view of [La] changes by visualising the behavior of lactate production and removal, and thus allowing the identification of the distance with a greater energetic contribution from anaerobic metabolism. Therefore, the aim of this study was to compare lactate peak and the area under the blood lactate concentration-time curve (AUC) at 50, 100, 200, 400, 800 and 1500 m in maximal efforts in youth swimmers performing front crawl.

Chart 1 Mean and SD values of [La] observed for distance of 50, 100, 200, 400, 800 and 1500 m. Not measured in the study

<table>
<thead>
<tr>
<th>Study</th>
<th>n and gender</th>
<th>Age (years)</th>
<th>Methods</th>
<th>Equipment</th>
<th>[La] (mmol·l⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sousa et al. (2011)</td>
<td>10</td>
<td>21.6 ± 2.4</td>
<td>1⁰, 3⁰, 5⁰ and 7⁰ min or until decrease</td>
<td>Lactate Pro analyzer (Arkray)</td>
<td>-</td>
</tr>
<tr>
<td>Vescovi et al. (2011)</td>
<td>50</td>
<td>20.2 ± 3.3</td>
<td>3⁰ and 5⁰ min</td>
<td>Lactate Pro analyzer (Arkray)</td>
<td>9.1 ± 1.9</td>
</tr>
<tr>
<td>Schnitzler et al. (2008)</td>
<td>8</td>
<td>18.2 ± 2.2</td>
<td>1⁰, 3⁰ and 5⁰ min</td>
<td>Lactate Pro meter (Accusport)</td>
<td>-</td>
</tr>
<tr>
<td>Avlonitou (1996)</td>
<td>54</td>
<td>21.6 ± 2.4</td>
<td>3⁰ and 6⁰ min</td>
<td>Automatic Lactate analyzer (YSI Company)</td>
<td>9.5 ± 2.2</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>16.7 ± 0.5</td>
<td></td>
<td></td>
<td>9.3 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>52</td>
<td>14.8 ± 0.4</td>
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<td></td>
<td>9.0 ± 2.0</td>
</tr>
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<td></td>
<td>32</td>
<td>19.3 ± 1.8</td>
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<td>10.7 ± 2.1</td>
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<td></td>
<td>63</td>
<td>16.3 ± 0.3</td>
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<td></td>
<td>9.3 ± 1.2</td>
</tr>
<tr>
<td></td>
<td>71</td>
<td>14.4 ± 0.5</td>
<td></td>
<td></td>
<td>9.3 ± 1.9</td>
</tr>
</tbody>
</table>

Materials and methods

Subjects

Twelve swimmers (15.6 ± 0.9 years old, 63.0 ± 7.2 kg body mass, 174.9 ± 8.3 cm height, and 180.7 ± 10.4 cm arm span; 280.2 ± 18.0 s as best short course 400 m freestyle time, corresponding to 79.0 ± 3.3% of the 25 m pool World Record over 400 m freestyle) volunteered to take part in this study. All swimmers had at least six years of experience in competition, and were training normally without interruptions during the collections. The protocol was approved by the University Ethics Committee and explained to the swimmers, who then gave their written consent to participate, which was signed by a legal guardian, since the participants were under 18 years old.

Swim trials

The protocol involved the performance in a randomised order of 50, 100, 200, 400, 800, and 1500 m all-out effort (24h interval). All trials were performed in front crawl with push start (25 m outdoor pool, with ≧29 °C and ≧31.5 °C for water and air temperature respectively). All performances were recorded at the nearest 0.01 s by two qualified timekeepers. Capillary blood samples (≦25 µl) for [La] analysis were collected from the fingertip of the hand after 10 min rest (Rest), after warm-up (Pre) (standardised, 800m freestyle) and after each all-out effort (recovery period: 1, 3, 5, and 7 min, or until [La]peak was identified) using Accutrend Plus (Roche®). AUC of [La] was calculated by the trapezoidal mathematical method, i.e., the sum of trapezoid areas, by the Equation 1:
where $b_1$ and $b_2$ are the lengths of each base, on the x axis, and $h$ is the height on the y axis. AUC of [La] was expressed as the percentage difference between each distance, with 50 m being 100%. Thus, for AUC calculation, just periods with data with all swimmers were used, so AUC was calculated until the third minute after the effort.

**Statistical analysis**

For all data, Shapiro-Wilk’s test was applied, since normality was confirmed, mean and standard-deviation were calculated. Data sphericity was verified with Mauchly test. Factorial ANOVA (six distances and three moments for [La] were applied). Main effects were verified with Bonferroni post-hoc test. When necessary, Greenhouse-Geisser Epsilon correction factor was applied. Effect size was verified with the $\eta^2$ test and statistic power was also calculated. When interaction between the factors was significant, one-way ANOVA for repeated measures was applied. Alpha was established in 5% and all the procedures were calculated in SPSS, v. 17.0. The lactate concentration curve ([La] curve) was identified by calculating the AUC for Rest, Pre, and recovery period (1, 3, 5 and 7 min) after each all-out effort (50-1500 m).

**Results**

Table 1 shows [LA] values (mmol·l$^{-1}$) at rest and pre, the comparison between different time assessment during recovery (1, 3, 5 and 7 min), the number of swimmers who reached [La] peak in each time of recovery assessment, the comparison between [La] peak (mean and SD) and the comparison of AUC of [LA] over time of 50, 100, 200, 400, 800 and 1500 m.
Table 1: Time of each event, [LA] values (mmol·l⁻¹) at rest and pre, the comparison between different time assessment during recovery (1, 3, 5 and 7 min; (*p < 0.05) with the number of swimmers who reached [LA]_{peak} in each time of recovery assessment, the comparison between [LA]_{peak} (mean and SD) of 50, 100, 200, 400, 800 and 1500 m (*p < 0.05; *, ** and & p < 0.01) and the comparison of AUC of [LA] over time (expressed as percentage difference between each event, with 50 m assumed as 100%).

<table>
<thead>
<tr>
<th></th>
<th>Rest</th>
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<th>AUC</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1 min</td>
<td>3 min</td>
<td>5 min</td>
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<td>7/12</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>100 m</td>
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<td>3.01</td>
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<tr>
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<td>±2.19*</td>
<td>±2.93*</td>
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<tr>
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<tr>
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<td></td>
<td>±0.76</td>
<td>±0.61</td>
<td>±1.74*</td>
<td>±2.04*</td>
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<td>n° of swimmers who reached [La]_{peak}</td>
<td>12/12</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>400 m</td>
<td>3.58</td>
<td>3.22</td>
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<td>8.92</td>
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<td>5/12</td>
<td>-</td>
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<tr>
<td>1500 m</td>
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<td>8.15</td>
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<td>±0.87</td>
</tr>
<tr>
<td></td>
<td>n° of swimmers who reached [La]_{peak}</td>
<td>9/12</td>
<td>3/12</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 1 shows the AUC of [LA] over time of 50, 100, 200, 400, 800 and 1500 m.
Discussion

The aim of this study was to compare lactate peak and AUC values after maximal efforts of 50-1500 m in front crawl in youth swimmers. In swimming, it is suggested that [La]_{peak} values are found between the 5th and the 8th minute into recovery (Di Prampero 1978). Other investigators have reported [La]_{peak} taking blood samples between 3 and 5 min (Sawka et al. 1979, Bangsbo et al. 1994, Keskinen et al. 2007) while Bonifazi et al. (2000) observed [La]_{peak} around 6-7 min after competitive events. In the present study, the time to reach [La]_{peak} had little variation between each event, standing mostly between 1-3 minute.

The high cost of the lactate strips sometimes limits the number of collection periods (1, 3, 5 and 7 min). This study also identified that different events have different recovery periods. Thus, this result can serve as a reference for coaches in future collections, i.e., the results suggest that, for practical purposes, it is useless collecting blood samples until the seventh minute in some events (50, 100, 200 and 1500m, Table 1) in competitive youth swimmers.

The highest values of [La]_{peak} are usually found following 100 and 200 m events (Sawka et al. 1979, Bonifazi et al. 1993, Avlonitou 1996, Schnitzler et al. 2008, Sousa et al. 2011, Vescovi et al. 2011), and this was confirmed by the present study (Table 1). The highest [La] observed in 100 and 200 m indicates a high glycolic contribution in these race distances. Factorial ANOVA showed no difference between [La]_{peak} after 100 and 200 m, but AUC showed a difference of + 3% (coefficient of variation of 3.82%). AUC identified the 100 m as the distance with greater contribution of anaerobic metabolism. In fact, Gastin (2001), using mathematical modeling techniques, suggested that maximal performances until 75 s need more contribution of anaerobic than aerobic metabolism. This technique could be useful to evaluate the rest period of a specific event during training sessions.

Conclusion

[La] assessments remain very important in swimming performance evaluation. Alternatives for its application and understanding of the results are always welcome for coaches. Area under the curve (AUC) of [La] may be applied in swimming. The highest [La] observed in 100 and 200 m indicates the highest glycolytic contribution between 50-1500 events. Factorial ANOVA found no difference between [La]_{peak} of 100 and 200 m, but AUC showed difference of + 3% between 100 and 200m.
Acknowledgment

The authors would like to thank, Rodrigo Carlet, Jessy Lauer, swimmers and Coaches Mirco Cevalles and Christiano Klaser for the relevant support. Rodrigo Zacca acknowledges Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—CAPES (Brasil) for the MSc Grant.

References


7 Physiotherapy

Spatiotemporal characteristics of walking on land and in water: reliability of measurements and analysis of differences

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¹Department of Physical Education and Sport, Faculty of Sport Sciences, University of Granada, Spain

Introduction

Human walking, defined as step biped used by the human being to move from one place to another, with minimal effort and minimal energy consumption, is a feature that allows to reveal aspects and individual parameters, health status, self-esteem and emotional situations of each person (Hicheur et al. 2013). In this regard, gait is a major sign of independence, quality of life and participation (Schmid et al. 2007) and is frequently impaired by a variety of musculoskeletal and neurological conditions or diseases (for example, stroke, cerebral palsy, multiple sclerosis or osteoarthritis) (Patterson et al. 2012). Improvement of the walking function is a common goal stated by patients undergoing rehabilitation (Patterson et al. 2012), specifically it is the number one in patients with stroke.

To improve the locomotion system, exercises are mainly carried out on dry land although now numerous activities have been proposed in the water environment. From a biomechanical point of view, there are two principal reasons why walking in water may be beneficial: the lowering of apparent body weight due to the buoyant force and the increased resistance to movement due to the drag force exerted by water on the human body (Orselli & Duarte 2011; Chevutschi et al. 2009; Barela & Duarte 2008; Barela et al. 2006). Specifically, forward walking (FW) may be one of the most common motor tasks in both environments because it can be practiced by any age-group and with most medical conditions (Chevutschi et al. 2009; Barela & Duarte 2008). In the clinical setting, kinematic gait variables are the most common objective measurements performed. In particular, frequency and length of one stride cycle is the most widely reported measure on land based studies, but few authors appear to have investigated the kinematics of forward walking in both conditions (on land and in water) (Carneiro et al. 2012).

In summary, gait measurement is essential for understanding the particular deficits exhibited by a patient, guiding clinical decision making, customising treatment and monitoring the effectiveness of a gait intervention (Patterson et al. 2010; Patterson et al. 2012). For these reasons, a study of the locomotion biomechanics, their exploration and further analysis is an essential tool that reveals the motor possibilities of the subject, spatial, temporal and angular variables that will help us to make a diagnosis, identify the deficiencies of body functional and specific limitations on the gait in order to achieve optimal work programs to benefit the health and quality of life of the subjects. However, to our knowledge, there is a striking lack of information about kinematics and spatiotemporal characteristics of gait when walking forward in water and on land applying three-dimensional motion analysis.

As a result, the biomechanics of movement while walking both on land and in an aquatic environment needs to be better described so that health care professionals have a scientific foundation on which to base their prescriptions of this activity as a therapeutic exercise. The purpose of this study was to compare the spatial and temporal characteristics in FW walking on land and in water.
Method

Participants

Eight young adults (four males, four females) volunteered to participate in the study. Their mean age, height and body mass values were 22.00 ± 0.81 years and 22.25 ± 1.50 years, 181.6 ± 0.06 cm and 168.0 ± 0.06 cm, 73.75 ± 6.65 kg and 59.00 ± 5.77 kg for male and female respectively.

Inclusion criteria were age between 20 and 25 years and familiarity with a water pool through aquatic exercise or swimming. On the other hand, exclusion criteria were presenting a neurological or musculoskeletal disorder at the time of the study, presenting a loss of balance or reporting pain in the lower limbs during walking. None subjects presented any impediment and all participants signed consent after being previously informed about the study procedure. The study was approved by the Ethical Committee of the University of Granada (8 January 2013; nº 776).

Experimental procedure

On dry land and in water, the subjects were requested to cover in a randomised order a distance of 10 meters at comfortable speed (controlled by a digital metronome –Korg TM-50– at eighty pulses per minute for land and 50 pulses per minute for water condition). To avoid the interference of the upper limbs, subjects walked forward with arms crossed at the chest (Carneiro et al. 2012).

Twenty-one passive reflective markers were placed on each participant’s right and left side at the following points: big toe, first and fifth metatarsal head, calcaneus, lateral malleolus, mid-lateral side of the tibia, femoral epicondyle, mid-side of the thigh, greater trochanter, sacrum and on top of the iliac crest. To obtain the kinematics data in water and dry conditions, participants wore specific running tights adapted to their anthropometric profile on which the markers were placed with hook and loop tapes (Velcro) and in those part where the pant did not cover the body (feet) they were fixed with a black adhesive tape (Farmafix) (Figure 1).

Figure 1  Frontal and lateral views of positions of anatomical markers

Before any measurement, participants performed several trials to familiarise themselves with the instrument (metronome), the modality of walking and the experimental environment. They were considered adapted when they could maintain their balance and showed coordination between the pulses of metronome and their steps. The number of trial required for the familiarisation was between four and six. Data were collected on two different days using the same procedures, due to the venues location. Each subject completed the entire test within a single day. The temperature was set at 24 ± 1ºC on land and 30 ± 1ºC in water. Specifically, in water the trials were performed in a
swimming pool 10m x 8m and 1, 20 m deep. Such as depth allowed the subjects to be immersed up approximately at xiphoid process level.

The participant’s movement on the sagittal plane (principal plane of movement) was recorded at 60 Hz (HD 1280x720 and shutter speed 1/1000) with four digital cameras (1J1, Nikon VR 10-30 mm lens) to obtain the measurements. The video images were synchronised through an external flashing light (about 1Hz). This experimental setup allowed us to perform a standard 3D analysis. The digitalisation of all markers, reconstruction, filtering and posterior analysis was performed using the Kwon3D Software (VISOL, Inc.). The real coordinates were reconstructed using a direct linear transformation (DLT) algorithm in the land condition and a localised DLT algorithm to account for refraction in the water condition (Kwon 1999, 2006).

**Data analysis**

The data were digitally and differentiated using five motion events: initial right heel-strike (RHS), left toe-off (LTO), left heel-strike (LHS), right toe-off (RTO) and the next right heel-strike (RHS2) (Figure 2). Among these, RHS is the start event and RHS2 the end event (one cycle). The landmarks were manually digitalised. The original coordinates were filtered using a Butterworth type low-pass filter with a cut-off frequency of 6 Hz and 2nd order. Each anatomical marker digitalised/filtered allowed us to calculate position, velocity and angle degrees of each segment in three axis: X (mediolateral - rightward-), Y (anteroposterior - forward-) and Z (longitudinal –upward-). All the gait cycles were normalised in time from 0% to 100% with a step of 1%.

The following variables were computed: speed, stride length, symmetry of step length and support phase duration. In order to assess the reliability of digitising, we calculated the intra-observer ICC ranged 0.97 to 0.99 and inter-observer ICC ranged from 0.98 to 0.99. These results showed a high correlation and reliability.

**Statistical analysis**

Mean and standard deviation (SD) were used to represent the average values of the studied variables. The spatiotemporal characteristics of the two environments were compared using repeated measures
ANOVA. The level of significance was set at $p<0.05$. This statistical analysis was made using SPSS software version 21.0.

**Results**

On land, the speed was greater than in water ($0.88 \pm 0.07$ vs. $0.62 \pm 0.03$ m/s) [$p<0.001$]. There were significant differences in stride length between environments. During FW walking, the stride length was higher on land than in water ($1.23 \pm 0.12$ vs. $0.90 \pm 0.08$ m) [$p<0.001$]. Regarding the symmetry of step length, relevance differences were observed in environments. In water, subjects were 23% more asymmetry than on land. Overall, support phase duration was smaller in water, with a decrease of 5.5%, compared to on land ($66.4 \pm 2.12$ vs. $60.9 \pm 2.81$).

**Conclusions**

The effect of the hydrodynamic resistance in water conditioned the stride length and therefore, the speed in water was lower than on land. Also, the buoyancy force determined that a less support phase duration. The hydrostatic pressure combined with the water drag could modify the symmetry of the step length in water.

Furthermore, this information provide a more precise point for the development of rehabilitation programs in water and on land for adults, detect problems with humans locomotion and may be used to therapists and clinicians to prescribe and select the correct treatment keeping in mind the adaptation of the exercises and the characteristics of the executions to the intervening forces in the water: resistance, flotation, pressure and propulsion. Future research required analyzing the current variables in pathological populations and at backward walking.

**Acknowledgment**

This work was supported by an initiation grant to research of University of Granada awarded to Cristina Cadenas. The authors wish to thank the CTS-527 research group members for their implication in this project. They also gratefully acknowledge the collaboration of all participating subjects.

**References**


Changes in the conditioning components for the Japanese Universiade swimming teams

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Keywords: physical therapy, injury prevention, athletic trainer

Introduction

Most injuries occurring in competitive swimmers are caused by overuse. Some studies have reported injuries in competitive swimmers. In Japan, Muto et al. conducted medical checkups for national team swimmers who participated in the 1990 Asian games. They reported that 68.8% of swimmers had injuries and that the low back region was the most frequently affected body part (1992, Written in Japanese). In addition, 56.1% of swimmers who participated in the 2008 Olympic games had injuries, with the low back region being the most frequently affected.

In contrast, injury survey reports for the national swimming team of the United States have mentioned that approximately 70% of national team swimmers had shoulder girdle injury and that 57% of swimmers who participated in the world championship games had shoulder girdle injury². Thus, the prevalence of injury and the injured parts are different even among top swimmers. This discrepancy may be caused by the differences in the support system of each country.

The Japan Institute of Sports Sciences (JISS) and the National Training Center (NTC) were established as centers for sports sciences, sports medicine, and information. The JISS promotes research activities and provides support for athletes and sports instructors, in cooperation with the Japanese Olympic Committee, sports federations, universities, and sports research institutions and organisations. The NTC is also a base for strengthening the performance of top-level athletes, enabling them to undergo intensive continuous training. The national swimming team also uses the facilities and support systems of JISS and NTC. Since 2001, the national swimming team has performed training camps at the JISS and NTC to improve competitive level and conditioning. These efforts help to not only improve competitive level but also prevent injury in swimmers. Because of these support activities, the incidence and locations of injuries have changed; however, these details have not been reported. In addition, it is important to longitudinally analyze conditioning components and the number of conditioning techniques used while developing injury prevention programs for swimmers.

Because most previous studies among swimmers were cross-sectional surveys, data verifying the effects of injury prevention programs and the conditioning components for swimmers are insufficient. The present study aimed to verify the longitudinal changes in the type and number of conditioning components for high-level Japanese swimmers.
Methods

The subjects included members of the Japanese national swimming teams that had participated in the Universiade competitions held at Belgrade, Serbia in 2009 and at Kazan, Russia in 2013. Data on conditioning components and the number of body parts treated by trainers were aggregated. In this study, we used a unified questionnaire form created by the Japan Swimming Trainer Committee (JSTC). This form included a column on bodily parts that swimmers wanted to treat and the conditioning components that the swimmers requested. The bodily parts column consisted of ‘Whole body’, ‘Head-back’, ‘Shoulder (included scapulothoracic joint)’, ‘Upper extremities’, ‘Lumber-pelvic’, and ‘Lower extremities’. The conditioning component column consisted of ‘Massage’, ‘Stretch’, ‘Physical modality’, ‘Acupuncture’ and ‘Physical evaluation and exercise’. The percentage of the total items was calculated and compared for each Universiade game.

Results

Three trainers were used in the games held in 2009 and 2013. The competition was held for 7 days, and the adjustment period was 10 and 12 days in 2009 and 2013, respectively. There were 37 and 38 swimmers in 2009 and 2013, respectively. Further, 343 and 486 conditioning components were used in 2009 and 2013, respectively. Table 1 shows the ratio of body parts that were treated, whereas Table 2 shows the ratio of the conditioning components in these 2 games. Figures 1 and 2 show changes in the number of treatments during the games held in 2009 and 2013, respectively. ‘Whole body’ (71.1%, 30.3%) was the most frequently treated body part. The ‘Shoulder’ (11.1%, 26.7%) was the second, and ‘Lumber-pelvic’ (8.7%, 19.6%) was the third in 2009 and 2013. ‘Stretch’ (2.7%, 26.5%) and ‘Physical evaluation and exercise’ (5.4%, 20.0%) were the second and third most common conditioning components performed following ‘Massage’ (71.1%, 30.3%) in each year.
Figure 2  Transition in the number of treatments during the games held in 2009

Figure 3  Transition in the number of treatments during the games held in 2013

Table 1  Ratio of the body parts treated in 2009 and 2013

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<thead>
<tr>
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<tr>
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<tr>
<td>Head–back (%)</td>
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<tr>
<td>Shoulder (%)</td>
<td>11.1</td>
<td>26.7</td>
</tr>
<tr>
<td>Upper extremities (%)</td>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Lumbar–pelvic (%)</td>
<td>8.7</td>
<td>19.6</td>
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<tr>
<td>Lower extremities (%)</td>
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Table 2  Ratio of the conditioning components in 2009 and 2013

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<thead>
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<th>Component</th>
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<th>2013</th>
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</thead>
<tbody>
<tr>
<td>Massage (%)</td>
<td>88.7</td>
<td>49.1</td>
</tr>
<tr>
<td>Stretch (%)</td>
<td>2.7</td>
<td>26.5</td>
</tr>
<tr>
<td>Physical modality (%)</td>
<td>2.1</td>
<td>0.9</td>
</tr>
<tr>
<td>Acupuncture (%)</td>
<td>1.1</td>
<td>3.6</td>
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<tr>
<td>Physical evaluation and exercise</td>
<td>5.4</td>
<td>20.0</td>
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Discussion

Previous studies have reported that many competitive swimmers have lower back and shoulder girdle injuries. Kaneoka et al. and Hangai et al. reported that they identified lumbar intervertebral disk degeneration in approximately 70% of the top-level competitive swimmers, and that this rate was significantly higher than that reported for players involved in other sports (basketball, football, etc.). Therefore, it is necessary to continuously analyze the causes of injuries in order to be able to prevent injuries that may occur in the future.

Cooperative and appropriate activities for the local and global muscles adjust the joint movements in the right directions. Therefore, it is important to strengthen the local muscles to prevent injuries of the lower back region and shoulder girdle. Currently, Japanese swimmers perform dryland training to improve the stability of the trunk region and mobility of the extremities as well as to increase the coordination between these regions and adjust the timing and ratio of these muscle activities. Swimmers requested for almost only massages during competitions. However, as the results of this study indicate, such training and efforts increase the requests from swimmers for physical evaluation and exercise.

Currently, massages are very effective in helping swimmers to recover from fatigue rapidly. However, the results of this study reveal that the relative ratio of the demand for massages has decreased, whereas that for physical evaluation and exercises has increased over these 4 years. Our findings suggest that swimmers try to recovery from fatigue by themselves as far as possible, which reflects the change in the perception of swimmers regarding self-conditioning. Trainers, coaches, and other staff working in the JISS have contributed greatly to this change.

Thus, our efforts have been effective in changing the perception regarding self-conditioning for swimming. However, the total number of swimmers who depend on trainers has increased over these 4 years. This finding may be influenced by the fact that the Universiade swimming team in 2013 also included swimmers who were elected for the first time in the national team. Therefore, it is important
to instruct swimmers of all levels and ages to exercise regularly in order to improve conditioning and enable them to become more independent and better swimmers.

**Conclusion**

The findings of this study revealed that the demand for massage decreased and that the demand for physical evaluation and exercises increased over the 4 years. Further, self-conditioning was found to be very important for swimmers. Our results, which suggest that the Japanese injury prevention program is effective, will be useful while developing programs for increasing the independence and strength of swimmers.

**Acknowledgments**

The researchers would like to thank the Japan Swimming Federation and the Japanese Universiade swimming team for their assistance.

**Reference**

8 Social sciences, humanities and pedagogics

Can you swim? Teaching teachers of swimming and water safety

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¹Federation University Australia (formerly University of Ballarat)

Keywords: water safety, swim teacher education, aquatics education, drowning prevention, program evaluation

Introduction

In the Australian state of Victoria, the education system for teacher registration via the Victorian Institute of Teaching (VIT) requires all secondary education ('high school') physical education teachers to provide evidence of a recognised teaching of swimming qualification (VIT 2008). Some Victorian Universities require only that pre-service physical education teachers complete the AUSTRWIM Teacher of Swimming and Water Safety course. Others include a unit or units of study in aquatics within their Bachelor of Education (Physical Education) (BEd Phys Ed) (or similar), which go beyond the minimum requirements of the AUSTRWIM award. Federation University Australia (Fed Uni, formerly the University of Ballarat) is one such institution, and requires its BEd (Phys Ed) students to complete two courses of study in aquatics, while the Bachelor of Exercise and Sport Science (BExSS) students at Fed Uni must complete one such unit of study. These compulsory courses of study provide an interesting cohort of study participants, as the entry level of aquatics skills varies widely among students as does student aquatic confidence.

Many of these students go on to teach swimming, either in schools, or through industry-based providers. The learning experiences of learn-to-swim teachers contribute considerably to the teaching strategies and program content that they implement when they go on to the role of aquatics teacher (AUSTRWIM 2008). By exposing our students to a comprehensive aquatics education experience, we aim to prepare students with enhanced understanding of knowledge, attitudes and behaviours that contribute to drowning prevention; improved personal swimming and survival skills; and the capacity to implement teaching strategies and sequences to facilitate others in learning aquatic skills. The benefits of our aims are that following completion of our units of aquatics, students should be better equipped for their own aquatic safety, as well as better prepared to teach others.

Little empirical research has been published to demonstrate a link between improved swimming capacity (through learn-to-swim instruction) and decreased drowning rates despite the oft made assumption that swimming proficiency is protective of drowning (Moran et al. 2012; Smith 1995). While there has been a vast expansion of learn-to-swim programs, at least in developed countries (American Red Cross 2004; Landendorfer 2008; Royal Life Saving Society Australia 2010), Langendorfer (2008), as Editor of the International Journal of Aquatic Research and Education, challenges us to conduct well-designed research to establish an evidence base regarding the role of swim lessons in drowning prevention. This paper, part of the broader Can You Swim? Project (for example, Moran et al. 2012; Petrass et al. 2012) details the methodology of ‘teaching teachers’ as a drowning prevention strategy.

Method

Overview

As part of the broader ‘Can You Swim’ project, we performed an evaluation of our first year aquatics unit Swimming, Water Safety and Aquatic Activity to determine the water safety knowledge, attitudes and swimming skills of our commencing students; and to establish the effect of a 12-week swimming and water safety intervention on the water safety knowledge, attitudes and aquatic competencies of
these students. A validated survey was conducted to determine pre-intervention knowledge and attitudes, as well as self-perception of aquatic skill level. Practical assessment of skills was also conducted, and demographic information obtained. Knowledge, attitudes and skills were re-tested using the same instruments at the conclusion of the intervention. The results that detail the evaluation of this program are explained elsewhere (paper Preventing adolescent drowning: Understanding water safety knowledge, attitudes and swimming ability. The effect of a short water safety intervention, currently under review) and demonstrate positive findings, at least in terms of knowledge and skills (little change was evident in attitudes). This paper focuses on the nature of the intervention, and provides brief statistical analysis of the data.

The intervention was structured as a 12 week swimming course conducted across one semester, with two 50-minute practical classes and one 50-minute theory class each week. Practical classes were held in groups of up to 30 students with two university staff, experienced in teaching aquatics, as instructors. Students were required to meet a 90% attendance criterion for practical classes. Injured or ill students who attended their practical class and participated from the pool deck were considered to be present. These students were able to practice in-waterskills in their own time to ensure familiarity with skills that were covered during the classes they observed.

Theory classes were conducted as lectures, with up to 154 students present. These classes were not compulsory and attendance was not measured. However, as theory and practical components of the unit each contributed 50% to final assessment, and a satisfactory standard was required in each of these components, most students attended. A blended delivery was implemented, with lecture notes and supplementary materials (for example, readings; links to websites; video clips; quizzes and revision questions) made available via the student on-line learning platform. Students also completed a workbook which included questions and material relevant to theory and practical classes. Table 1 provides a brief summary of topics addressed during theory and practical sessions.

Philosophy

The first year aquatics unit of study aimed to provide a comprehensive approach to aquatics education. It addressed water confidence; aquatic survival skills; competitive swimming skills; and aquatic rescue (including initiative tests/rescue scenarios). We covered the comprehensive learn-to-swim practical curriculum over only 24 sessions due to the time constraints of the degree curriculum, although the 10 credit point unit expected students to undertake a total of 100 learning hours, including their study and practice outside of class. The theory lectures and supplementary on-line material supported the practical curriculum and students were encouraged to undertake at least four half-hour in-water practice session each week. Two optional additional sessions were conducted weekly for students who wanted further assistance and 5-10% of students typically sought this help.

In practical classes throughout the course, student attention was drawn to teaching strategies and sequences, as the aim was not just for students to improve their personal performance, but also for them to develop skills in teaching others. Participative learning ensured a collaborative learning pedagogy was established. Students typically worked in pairs or small groups and emphasis was placed on small group discussion and ideas exchange to facilitate active learning. In this setting, students were required to observe each other, analyse the technique of others and implement teaching strategies to assist their peer/s in the correction of faulty technique. The teaching staff assisted in this process, typically through the use of questioning to help students in the correction process. This learning approach has been considered a successful method to enable students to learn and retain information more effectively than when working individually (Totten et al. 1991; Johnson & Johnson 1986).
Table 1  The teaching sequence and content included in the 12-week intervention program

<table>
<thead>
<tr>
<th>Week</th>
<th>Theory sessions</th>
<th>Practical 1</th>
<th>Practical 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction to swimming and water safety</td>
<td>Water confidence games; Breathing</td>
<td>Body orientation; Basic Sculling</td>
</tr>
<tr>
<td>2</td>
<td>Drowning epidemiology</td>
<td>Survival Sculling, sculling for movement; synchronised swimming skills</td>
<td>Backstroke</td>
</tr>
<tr>
<td>3</td>
<td>Fluid mechanics</td>
<td>Backstroke continued</td>
<td>Freestyle</td>
</tr>
<tr>
<td>4</td>
<td>Fluid mechanics</td>
<td>Freestyle continued</td>
<td>Breaststroke kick, survival backstroke</td>
</tr>
<tr>
<td>5</td>
<td>Entries, focusing on teaching safer diving skills</td>
<td>Breaststroke continued</td>
<td>Entries; safe diving skills</td>
</tr>
<tr>
<td>6</td>
<td>Survival issues &amp; techniques</td>
<td>Sidestroke</td>
<td>Survival skills (clothed); PFDs; HELP and Huddle positions</td>
</tr>
<tr>
<td>7</td>
<td>Survival issues &amp; techniques</td>
<td>Practical survival test</td>
<td>Butterfly</td>
</tr>
<tr>
<td>8</td>
<td>Starts and turns</td>
<td>Butterfly continued</td>
<td>Competitive starts and turns</td>
</tr>
<tr>
<td>9</td>
<td>Rescue</td>
<td>Introduction to rescues: rope throw; dry rescue</td>
<td>Victim simulation; defence and escape positions</td>
</tr>
<tr>
<td>10</td>
<td>Spinal injury management</td>
<td>Accompanied rescues; Non-contact rescue</td>
<td>Contact rescues &amp; Spinal cord injury management</td>
</tr>
<tr>
<td>11</td>
<td>Aquatic instruction &amp; Designing sessions for different settings</td>
<td>Initiative and judgement</td>
<td>Initiative and judgement</td>
</tr>
<tr>
<td>12</td>
<td>Revision of qualitative analysis of swimming strokes</td>
<td>Squad organisation and training practical</td>
<td>200m individual medley time trial</td>
</tr>
</tbody>
</table>

**Practical classes**

The first three practical sessions addressed water awareness and confidence, through games, body orientation activities and sculling activities. The importance of ‘feeling comfortable in the water’ and ‘having fun’ was highlighted and students were reminded that in the real world, unlike the compulsory nature of their course, learners would only be successful in developing aquatic skills if they chose to continue to attend. Developing confidence in the water and having fun are important for this to occur. It was also emphasised that even though they were participating in aquatic play during these early sessions, the survival skills of body orientation and survival sculling were being developed, skills that are vital in an aquatic emergency. Likewise, through the early development of sculling, the fundamental skill underpinning propulsion in all strokes was established.

The development and improvement of swimming was facilitated by the transfer of the already established sculling skills. Backstroke was the first stroke addressed, for several reasons. For many in the Australian population, ‘swimming’ means freestyle (or front crawl) and some parents believe that once their child has learnt to swim freestyle for 25 metres, no further aquatic education is required. By introducing a stroke other than freestyle as the first stroke, the benefits of non-freestyle strokes can be discussed. The first two authors of this paper have a long history of experience in teaching aquatics and have observed that for some learners who are not comfortable to submerge their face, commencing stroke development with backstroke facilitates learning success. For these learners, propulsion skills can be developed without the discomfort of face submersion. As they progress in backstroke, these less confident learners become more comfortable in the water. The ensuing increase in confidence means they become happier to put their face in the water and thus learning freestyle and breaststroke becomes less difficult. In the perfect setting, the choice of stroke to teach first would be based on learner confidence and preference. In the University setting, however, when a group of up to 30 students needs to progress through a busy curriculum in limited time, there are time efficiencies in using a more directed sequence of topics.

Following backstroke, freestyle and then breaststroke (including survival and rescue backstroke) were covered. For our students, we have found the need to spend more time on breaststroke than other strokes, as we insist on a correct and efficient technique. A proportion of our student learners arrive
with significant technique errors in breaststroke and thus we apportion more time to this stroke to allow increased practice and instruction time for students working in pairs or groups to help each other to improve their technique.

We spent a session on entries and teaching safer diving before we commenced sidestroke. This is because of the potential for negative transfer between sidestroke and breaststroke kicks, for those learners still working towards technique improvement in breaststroke. The most common, and stubborn, error we observe in breaststroke technique relates to inadequate eversion and/or dorsiflexion in one or both feet. The difference in the position of feet for sidestroke can cause confusion for students yet to master breaststroke. By providing a little more time for students to practice out of class and establish the correct breaststroke technique before moving on to sidestroke, we believe student success is enhanced. Typically, students learn sidestroke very quickly and only one class was dedicated to this stroke.

After the basic strokes of backstroke, freestyle, breaststroke and sidestroke, students were introduced to clothed swimming and survival techniques. A survival scenario simulating a boating mishap was used to prepare students for the possibility an aquatic emergency and students were required to successfully complete the scenario as part of their assessment for the unit. Table 2 outlines this task.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Survival assessment scenario (performed in swimwear, long trousers, long sleeved shirt, pull-over top, shoes and socks, and in a continuous sequence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Dive and swim 10 m underwater to simulate an escape from a sinking boat surrounded by oil.</td>
</tr>
<tr>
<td>2.</td>
<td>Swim a further 40 m front crawl as if escaping from a dangerous situation.</td>
</tr>
<tr>
<td>3.</td>
<td>Remove shoes while treading water if desired, and then swim slowly 50 m breaststroke.</td>
</tr>
<tr>
<td>4.</td>
<td>Float, survival scull or tread water for 5 minutes and demonstrate waving one arm occasionally as if signalling for help; reassure any nearby candidates by talking to them.</td>
</tr>
<tr>
<td>5.</td>
<td>Swim slowly for 200 m using survival strokes, changing after each 50 m to another stroke.</td>
</tr>
<tr>
<td>6.</td>
<td>Remove clothing in deep water.</td>
</tr>
</tbody>
</table>

The next topic was competitive swimming and students spent a total of three sessions on butterfly, starts and turns. Further time was allocated to competitive swimming in the final week of semester, where a modified squad session was undertaken, to help students with an understanding of organisation and training for swimming. Likewise, each class took part in a simulated 200m individual medley time-trial, to ensure students had at least one competitive swimming experience.

Six practical class sessions were allocated to rescue and included victim simulation, dry rescue, accompanied and non-contact towing, contact rescues and spinal cord injury management. Two sessions were dedicated to initiative tests/rescue scenarios where students took part in rescues as rescuers and as simulated victims. Those students not directly involved in the simulation acted as observers. Following each scenario, a debrief dialogue took place and students discussed good and poor aspects of the rescue and considered methods for improving the rescue. Students took turns as rescuers, victims and observers, and all were expected to contribute to the debrief discussion. Participation in rescue scenarios provided the opportunity for students to implement their skills in a more ecologically realistic setting.

**Results and discussion**

Statistical analysis was conducted to compare pre- and post-intervention survey and practical data for the 135 students who took part in both data collections. Wilcoxon matched pairs signed ranks test was used for comparison between knowledge, swimming ability and attitudes scores pre- and post-intervention. These data are presented more fully in another publication currently under review. University based assessment (practical and theory) was conducted for all students as a further measure of successful completion of the intervention.
Significant improvement in practical skills (400m swim; 100m swim on back; underwater swim; dive) was demonstrated (p<0.001) and perceived swimming ability (rated via a 10 point scale) reflected this change (pre-intervention: M=6.95, SD=1.80; post-intervention: M=7.36, SD=1.44, p<0.001). Pre-intervention knowledge scores were low (M=37.2%), but improved significantly post-intervention (M=66.4%, p<0.001). There was no significant change in overall attitude scores (p=0.079), although when attitude statements were considered individually, one-third of statements were significantly different, becoming more conservative.

While 154 students commenced the semester, only 135 (88%) completed both the pre- and post-intervention data collection. The missing data related to students who had withdrawn from their degree program, were injured during the semester and unable to continue their participation, or were absent at the time of follow-up. Of the students who completed the unit (146 in total), only one did not pass. The provision of opportunities for additional support for less confident learners was an important factor for success. A small proportion of students were provided additional time to meet the practical competencies, and most did so within three months.

We believe the comprehensive nature of the intervention was vital to its success in improving student knowledge and practical skill competence. Likewise, the pedagogical approach, using active participation, critical thinking and collaborative learning (Totten et al. 1991; Johnson & Johnson 1986) also contributed to the intervention’s success. Working closely with partners in stroke analysis and correction helped students to develop their skills in technique analysis, as demonstrated by the university-based assessment of these skills (‘Credit’ average). It also contributed to their awareness of their own skill level, resulting in more realistic estimation of their capacities and risk. Further, while our practical classes took place only in a swimming pool, students were able to transfer their learning to other contexts, at least as demonstrated in their theoretical exam, where a range of questions required application of knowledge in different settings.

Having only 24 formal sessions was not sufficient for some students to feel confident that they would reach the required practical skills levels. A small number of students (3-10 each session) who considered their entry skills were low commenced additional practical support sessions conducted by the first author from the commencement of the semester. These sessions were highly flexible and the focus of each session was student driven. In the early stages, considerable time was spent on water familiarisation activities. Students were encouraged to try a range of activities designed for relaxation in the water. As the semester progressed, more students attended these sessions, with a peak of 29 immediately prior to the practical exam.

**Limitations**

Overall, this study illustrates that a short, comprehensive aquatics education intervention can improve participants’ practical swimming competencies and water safety knowledge, but there are a number of limitations to be considered. First, while the sample size was relatively large, participants were drawn from a cohort of exercise and sport science students. Accordingly, it could be anticipated that this group of young adults may develop practical skills more readily than the general population. Further, all exercise and sport science students in the group must pass this compulsory unit to complete their degree and are therefore highly motivated to succeed. Those among the group who do not enjoy aquatic activities continued in the intervention, while in a voluntary setting this might not be the case. Future investigations with a cohort more representative of the general population would add to these findings.

**Conclusions**

The short, comprehensive water safety intervention successfully improved the skills and knowledge of the student participants. While it is important to replicate these findings in a broader sample of participants, this study is the first to provide empirical evidence of the value of a comprehensive aquatic education program as a drowning prevention strategy for young adults.
Lane bias at the 2013 Swimming World Championships

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Keywords: athletic competition, analytics, performance, sport

Introduction

The Olympic Games and World Championships are the pinnacle of international sporting competitions where athletes compete in a wide variety of competitive events while representing their respective nations. However, as we watch these competitions, we do so under the assumption that each competitor’s success is determined solely by hard work, commitment, discipline, and talent, and not influenced by external variables or biases. To ensure that this is so, international governing bodies, such as FINA, IAAF, FIFA, and the International Olympic Committee (IOC), exist to ‘provide fair and drug free sport’. It is unfortunate, however, that there are circumstances when external biases unfairly influence sporting outcomes, and can only be identified ex post facto when it’s too late to protect the integrity of the competition.

The most obvious and evident of these external biases involves the competitors’ use of ergogenic substances to enhance their performance. Considerable effort and funding have been devoted specifically to curtail performance enhancing drug (PED) use, but the means to enforce the rules always seems to lag behind those used to disregard them (Botre 2008). Sport governing bodies must also consider advances in technology (e.g., equipment, uniforms, timekeeping) that sometimes challenge the inherent nature of the sport by unduly influencing competitive outcomes. For example, since the early 21st century, swimsuit manufacturers have experimented with different fabrics, shapes, and stitching techniques in an effort to provide competitive swimmers with the fastest swimwear. However, it was not until 2008 that a swimsuit innovation drastically biased Olympic competition in favor of those with access to them (Brammer et al. 2012). Like PEDs, the suits facilitated a swimmer’s intrinsic and natural ability to perform, and were subsequently banned in 2010. In 2010, design limitations were imposed by the sport’s international governing body, the Federation Internationale de Natation (FINA), to constrain competitive suit manufacturers as a means to re-establish competitive fairness. This example is particularly important because it demonstrates
that performance data can be described using analytical techniques, which can then be used to identify the existence (or lack) of competition bias. Further, this empirical evidence can prompt sport-governing bodies to act to remove the bias. This, the use of analytics to identify and remove competition bias, is the focus of this paper.

A recent scenario at the 2013 FINA World Swimming Championships in Barcelona presents another opportunity to use analytics to identify variables potentially influencing competitive outcomes. According to observers and participants, a current was present in the pool such that when swimming away from the finishing end swimmers were at a competitive disadvantage on one side of the pool but at an advantage on the opposite side. If there was, in fact, a current in the pool during competition, it would have violated FINA regulations which state that water flowing into and out of the pool is ‘permissible as long as no appreciable current or turbulence is created’ (FINA, 2013, p. 392). Because the competitive venue was temporary, it is no longer possible to directly measure the flow characteristics of the pool. However, quantitative analysis of existing performance data might allow appropriate conclusions to be drawn. Thus, the purpose of this study was to use an analytical approach to assess the performance data from the 2013 FINA World Swimming Championships. This was done in order to determine whether or not evidence exists in support of the hypothesis that swimmers’ competitive performances (and thus the race outcomes) were affected by lane assignment.

**Method**

The data for this study came from swim competition results from the 2005, 2007, 2009, 2011, and 2013 FINA World Swimming Championships, and were obtained from the Omega Timing website (http://www.omegatiming.com).

To determine if performances were facilitated or inhibited based on the lane in which the swimmer competed, we first took the difference between the mean odd and even 50-meter splits for each 1500-meter Freestyle performance. To eliminate the impact of the start and the tactical aspect of the finish, we did not include the 50-meter splits from the first or last 100 meters of the races. Next, we grouped the differences between odd and even 50-meter splits by lane. Then, we calculated the overall mean difference between odd and even 50-meter splits for all 1500-meter Freestyle performances. Finally, to determine whether or not each lane differed from the overall mean value, we performed one-sample t tests for each lane using the overall mean difference for all swimmers as the test value.

Our analysis on the 1500-meter Freestyle provided support of the hypothesis that a lane bias existed at the 2013 World Swimming Championships. And while it was clear that there was a lane bias that affected split times, it was unclear as to whether or not the bias impacted the final meet results. Logically, it would seem that any advantage a swimmer received from swimming in one direction would be counteracted by a disadvantage when swimming in the opposite direction. However, there are eight events at FINA World Championship competitions in which swimmers swim in only one direction (i.e., men’s and women’s 50-meter events). Since the swimmers only perform one length of the pool, the presence of a lane bias could have a major impact on the event results, especially if the bias affects swimmers differently in each lane. Based on our initial analyses of 1500-meter Freestyle splits, we hypothesised that the swimmers in lanes 5-8 would be at an advantage in the 50-meter events and the swimmers in lanes 1-4 would be at a disadvantage.

To test whether or not this apparent lane bias affected the performances in the 50-meter events, the percent change in prelim to semi-final performance time was calculated for the top-16 swimmers in each event, and the percent change in semi-final to final performance time was calculated for the top-8 swimmers in each event. The total sample was (8 events x 16 semi-finalists) + (8 events x 8 finalists) = 192 observations. Each observation was appointed to one of four lane change scenarios based on the swimmers’ lane assignment for each pair of swims (see Table 1). Again, from our previous analyses, we hypothesised that swimmers with their first swim in lanes 1-4 and second swim...
in lanes 5-8 (LH) would show the greatest improvement in performance and swimmers with their first swim in lanes 5-8 and second swim in lanes 1-4 (HL) would show the least improvement in performance. We tested our hypothesis by conducting a one-way ANOVA to determine whether or not the four groups were different with respect to the percent change in performance. In the event of a significant F-ratio, we planned to make all pairwise comparisons using Tukey’s HSD post hoc test. In addition, we performed the identical analyses on FINA World Swimming Championship data from 2005, 2007, 2009, and 2011 to determine whether or not the findings from the 2013 competition were unique.

Table 1

<table>
<thead>
<tr>
<th>Lane Group</th>
<th>Lane in First swim</th>
<th>Lane in Second swim</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL</td>
<td>1-4</td>
<td>1-4</td>
</tr>
<tr>
<td>LH</td>
<td>1-4</td>
<td>5-8</td>
</tr>
<tr>
<td>HL</td>
<td>5-8</td>
<td>1-4</td>
</tr>
<tr>
<td>HH</td>
<td>5-8</td>
<td>5-8</td>
</tr>
</tbody>
</table>

Note: For each swimmer, their first swim was either a preliminary swim or a semifinal swim and their second swim was either the semifinal or final swim, respectively. L = low numbered lanes, H = high numbered lanes.

Results

Figure 1 illustrates the mean difference between the odd and even 50-meter splits for each lane from the Men’s and Women’s 1500-meter Freestyle. The mean difference between the odd and even 50-meter splits from the 1500-meter Freestyle for all swimmers that completed the race in lanes 1-8 was -0.081 s, and this value was used as the test value for the one-sample t tests. The mean for each lane was significantly different from the overall mean, with lanes 1-4 significantly less than the overall mean and lanes 5-8 significantly greater than the overall mean. However, if we adjust the alpha level using the Bonferroni Correction to compensate for the number of comparisons (i.e., alpha = 0.05 / 8 = 0.00625), we find that difference between the odd and even 50-meter splits for lanes 1-3 was significantly less than the overall mean difference and the difference for lanes 7-8 was significantly greater than the overall mean difference.
Note: the dashed line represents the mean difference between the odd and even 50-meter splits in the 1500-meter Freestyle for all lanes and is equal to -0.081 s. * indicates the difference between the odd and even 50-meter splits for a particular lane was significantly different from the overall mean difference (P < 0.05).

Figure 1  The difference between the odd and even 50-meter splits from the 1500-meter Freestyle at the 2013 FINA World Swimming Championships as a function of lane

The percent change in performance from preliminaries to semifinals or from semifinals to finals for the four different lane groups is shown in Figure 2. One-way ANOVA indicated that the lane change scenario had a significant effect on the percent change in performance (F = 31.26, p < 0.001). Tukey's HSD showed that swimmers in LH improved significantly more than when swimmers were in HL, LL, and HH (p < 0.05). In addition, HL showed a decline in performance, and this was a significantly worse result than the three other scenarios (p < 0.05). HL from the 2013 competition was the only scenario from the past five World Swimming Championships that showed a significant decline in performance with advancing round for the 50-meter events (see Figure 3).
Note: swimmers that competed in lanes 1-4 or 5-8 for both swims were assigned to LL and HH, respectively; swimmers that competed in lanes 1-4 for their first swim and lanes 5-8 for their second swim were assigned to LH; and swimmers that competed in lanes 5-8 for their first swim and lanes 1-4 for their second swim were assigned to HL. * indicates that the percent change for a group lane change scenario was significantly different from the three other groups scenarios (P < 0.05).

Figure 2 The percent change in performance from preliminaries to semifinals or from semifinals to finals for the four lane change scenarios, which represent the lane assignments for the pair of swims, at the 2013 FINA World Swimming Championship.
Note: swimmers that competed in lanes 1-4 or 5-8 for both swims were assigned to LL and HH, respectively; swimmers that competed in lanes 1-4 for their first swim and lanes 5-8 for their second swim were assigned to LH; and swimmers that competed in lanes 5-8 for their first swim and lanes 1-4 for their second swim were assigned to HL. There was one occasion at the past five World Championships where a scenario showed a significant decline in performance (P < 0.05) and that was HL in 2013. All other groups showed a significant improvement or no change in performance.

Figure 3 The percent change in performance from preliminaries to semifinals or from semifinals to finals for the four lane change scenarios, which represent the lane assignments for the pair of swims, at the 2005, 2007, 2009, 2011, and 2013 FINA World Swimming Championships

Discussion

Elite competitive sport is assumed to be conducted in accordance with ‘the spirit of the game’, and not influenced by artificial or otherwise contrived biases. However, there are documented events whereby external biases have been shown to unfairly influence sporting outcomes, and other cases in which only the rumors of a bias persist. Obviously, a valid mechanism for identifying performance biases is paramount to the maintenance of fairness in competition. Fortunately, competition biases in sport can be identified through analysis of readily available performance data. And, this type of analysis can be used to mandate changes for the better.

For example, at the 1996 and 2000 Olympic track and field competition, the starting mechanism was shown to bias the competition outcomes in favor of the athletes positioned closest to the starter. Julin and Depena (2003) pointed out that sound travels through the air at a speed of approximately 350 ms\(^{-1}\). As a result, if the sound from the starter’s gun travels through air to the athletes, there will be a delay of about 0.03 s for every 10 m of distance between the starter’s gun and the athlete. This can put athletes in certain lanes at a competitive disadvantage for track events in which the athletes are staggered for the start. However, at the 1996 and 2000 Olympic Games, the sound from the gun discharge was supposedly picked up by a microphone and transmitted to a loudspeaker attached to
each starting block as a means to eliminate the lane bias due to the distance from the starting gun. Despite the use of this technology, researchers provided evidence that the athletes seemed to be responding to the sound of the gun transmitted through the air, not the sound transmitted through the loudspeaker system as was intended (Julin & Dapena 2003). As a result, athletes located farther from the starting gun were shown to be at a competitive disadvantage (Julin & Dapena 2003). To rectify this problem at subsequent Olympic Games, the ‘silent gun’ system was adopted, whereby the starting gun does not make any sound when the trigger is pressed. Instead, the starter initiates an electrical signal that is simultaneously transmitted to each starting block.

The application of the ‘silent gun’ is an example in which rules were changed for international competition based on post-hoc analysis of performance data. Similarly, the purpose of this investigation was to analyze meet results from the 2013 FINA World Swimming Championships in an effort to determine whether or not a current in the competition pool may have affected race outcomes. In our analysis of the evidence, we performed inferential procedures on the results of the 1500-meter Freestyle and the four 50-meter events. In doing so, we found that the results of all of our analyses were consistent with a current in the pool during the competition.

The analyses regarding the 1500-meter Freestyle provided initial evidence in support of the hypothesis that an external factor influenced performances differently on one side of the pool versus the other. The odd 50-meter splits from the 1500-meter Freestyle were faster than the even 50-meter splits in lanes 1-4, while the opposite was true in lanes 5-8 (Figure 1). This result is unexpected in an event in which the athletes typically attempt to maintain an even pace throughout most of the race. Figure 1 also demonstrates that the size of the effect varied by lane. The difference between odd and even 50-meter splits was negative for lanes 1-4 and became less negative when moving across the pool from lane 1 to 4. In contrast, the difference was positive in lanes 5-8 and became more positive when going from lane 5 to 8. This data seems to support the existence of the rumored current, illustrated by swimmers on one side of the pool being advantaged over those on the other side.

Like the results from the analyses on the 1500-meter Freestyle, the analyses on the 50-meter events for the four competitive strokes were consistent with the rumored pool current. The swimmers that completed their first swim in lanes 1-4 (swimming against the supposed current) and their second swim in lanes 5-8 (swimming with the supposed current) showed significantly greater improvement than swimmers that completed both swims in lanes 1-4, swimmers that completed both swims in lanes 5-8, and swimmers that completed their first swim in lanes 5-8 and their second swim in lanes 1-4. But what is typical for the change in performance in a 50-meter event when advancing from the preliminaries to the semi-finals or from the semifinals to the finals? If we compute the change in performance from preliminaries to semifinals or from semifinals to finals for each swimmer competing in the 50-meter events at the past five FINA World Swimming Championships, we find that, on average, swimmers improve by 0.26 ± 0.94% (N = 955). Knowing this, it is not a surprise to see that swimmers at the 2012 Championships significantly improved their performance when both of the swims were on the same side of the pool. LL swimmers improved by 0.19%, and HH swimmers improved by 0.43%. Importantly, while these improvements were significantly greater than zero, they were not statistically different from the mean improvement observed over the course of the five FINA World Swimming Championships from 2005-2013 (i.e., 0.26% improvement).

On the other hand, when a swimmer’s lane assignment switched from one side of the pool to the other with an advance in round (the LH and HL lane change scenarios), the results differed. LH swimmers improved their performances significantly more (1.11% improvement) than what we determined as being typical and representative (0.26% improvement). Their improvement was more than double that of any lane change scenario from any FINA World Swimming Championship competition held from 2005-2013 (see Figure 3). In contrast, HL swimmers were, on average, 0.59% slower than they were during the previous competitive round. This was the only lane change scenario in which swimmers swam slower in 50 meter events with advancing rounds at the FINA World Swimming Championships between 2005 and 2013 (see Figure 3). All other scenarios analyzed
showed a significant improvement or no change in performance. Consistent with the rumored current, we speculate that the reason LH and HL swimmers performed the way they did was because they went from being assisted, or alternatively, resisted by the current in their first swim to being resisted or assisted by it in their second swim, respectively.

If we accept this premise that swim performances were affected by a pool current, then logic would argue that one or more of the determinants of swim speed must be affected as well. Though the mechanics of human propulsion in the water are only partially understood, it is accepted that swim speed can be viewed as the product of stroke rate and distance per stroke (Craig & Pendergast 1979). It stands to reason, then, that stroke rate and/or stroke length must have been altered given the varying effects observed on swim performance from one side of the pool to the other. To better understand how performances at the 2013 World Championships were affected, segmental lap measurements of speed, stroke rate, and stroke length were recorded for every event by an external research group, and made available to the general public on the championship website. In parallel with our analysis of the 50-meter events, LH swimmers had between 2.5 and 3.4% greater stroke length than the three other lane change scenarios. Further, HL swimmers were between 1.5 and 2.5% slower than the three other lane change scenarios. While this evidence can only be considered circumstantial and we cannot, therefore, defend the accuracy, precision, and validity of these data, these results provide additional circumstantial evidence consistent with a lane bias and most likely caused by a pool current.

All the evidence from this study suggests that the meet results were dependent on lane position, a circumstance that should not happen at any sporting competition much less one of the magnitude of the World Swimming Championships. The only guidelines provided for the hosts of swimming competitions are that there should be ‘no appreciable movement’ of the water and ‘no appreciable current or turbulence’. But what qualifies as ‘appreciable movement’ and an ‘appreciable current?’ It certainly seems that if a current was present that biased the results, it would qualify as an ‘appreciable current’. However, as none of these analyses involved direct testing of the physical properties of the facility, we recognise that we can only hypothesise the cause of these analytic results.

Limited by our inability to retroactively measure the competition pool, we conclude that an external ‘bias’ existed at the 2013 World Swimming Championships such that swimmers’ performances were consistently affected depending upon which lane the swimmers were seeded. Additionally, due to the magnitude of the bias, we conclude that the competition outcome in certain events was likewise affected. The mechanism by which swim performances were affected appears to be consistent with alterations in stroke length. As there are no other reasonable explanations for these findings, there is strong evidence that the bias was as a result of a current in the pool. There may be other analytic approaches, and additional evidence from alternative swim events not analyzed here. Nevertheless, we hope that the evidence provided here will be cause for the swimming community to consider how similar lane biases might be prevented at future competitions. We recommend that FINA recruit the assistance of engineers and other pool design experts to assess and advise on the problem of currents in competitive swimming pools. From continued, informed dialog, new regulations can be put forth to fulfill one of FINA’s primary stated objectives: to provide fairness in competition.

**References**


Low-cost prototype development and swim velocity profile identification using neural network associated to generalised extremal optimisation

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Abstract

Velocity analyses are supportive for coaches in order to improve swimmers’ technique and have been widely studied in order to improve the athletes’ performance. This work presents a low-cost prototype development to measure swim velocity encompassing noise reduction by using a microcontroller associated with an incremental encoder. Swim velocity profile identifications have been performed by using a Radial Basis Function Neural Network (RBF-NN) improved by the stochastic Generalised Extremal Optimisation (GEO) method to provide a fast convergence. The proposed RBF-NN training is aimed at adjusting Gaussian basic function centres using GEO, which has just one free parameter to be set. It does not make use of derivatives and can be applied to non-convex or disjoint problems. Finally, the velocity data from a Brazilian elite male swimmer performing the crawl stroke have been obtained in a 25 meters test by using the prototype presented in this work. In this experiment, the pseudo-inverse was employed in the RBF-NN output layer. The proposed RBF-NN provided a multiple correlation coefficient R² equal to 0.84.

Introduction

By the interaction of propulsive and resistive forces, velocity can be increased and many research works in the competition area are considering this important variable to investigate the athletes’ performance (Toussaint 2002; Havriluk 2004; Wakayoshi et al. 2010; Arellano et al. 2010; Stamm et al. 2011; Coelho et al. 2013).

When velocity is related to other physical variables, e.g. hand forces, more information about the biomechanics of the performance can be provided resulting in significant contributions to training routines.

This work presents a low-cost prototype development to measure the velocity of athletes in swimming. It was developed as a data acquisition system that can be positioned outside the pool and be connected to the athlete through a nylon line. The prototype was used to collect data and a software was implemented to perform the swim velocity profile identification of a male elite athlete in a 25m crawl stroke by using a Radial Basis Neural Network (RBF-NN) associated to Generalised Extremal Optimisation (GEO) and expectation-maximisation (EM) clustering method optimisation methods. Both GEO and EM methods were used to enhance the flexibility of the RBF-NN by reducing the number of empirical variables to be configured thus enhancing the multiple correlation coefficient and providing a more reasonable velocity profile model.

The next section of this paper presents the prototype development followed by the system identification procedures in section 3. Section 4 describes the experiments and results in terms of model estimation. Finally, section 5 addresses the conclusions and the sequence of this work.

Velocity measurement prototype for swimming

In the swimming competition environment, it is possible to realise that small variations in velocity may make the difference between high level athletes where the technique is already well trained
and small details are difficult to notice, even by experienced coaches. However, to measure the velocity inside the pool it is necessary to take into account some factors as well the water environment and the possibility of real-time data acquisition.

Usually, sensors and electronic circuits must be insulated from water contact to avoid damage to the systems and, when real-time data acquisition is necessary, additional electronic technologies may increase the price of the system.

With the purpose of developing a low-cost tool to support the swim velocity profile identification, a real-time velocity measurement prototype was built using an incremental encoder concept, combined with a set of pulleys using a nylon line connected directly to the athlete through a belt (Figure 1-a). Software was implemented to provide mathematical treatment to the acquired data and provide a real-time plot. A physical device on the prototype equipment to support computing issues, a microcontroller ATMega168 from Atmel was used (Atmel 2011). This kind of configuration is a non-innovative way to measure the instantaneous velocity of the athlete during the swim, as a low-cost system that does not need to be waterproofed (the equipment should be positioned outside the water, over or beside the start block), (Figure 1-b). Moreover, by using a user-friendly interface, the system is capable of providing real-time velocity graphs to coaches during training routines.

![Velocity measurement prototype](image1.png) ![Data acquisition system](image2.png)

**Figure 1** (a) Velocity measurement prototype; (b) Data acquisition system positioned on the start block

The operation of the velocity measurement prototype can be described as follow:

**Step 1:** Real data acquisition. The athlete wears a belt on your waist which will pull out the nylon line during swimming. The set of pulleys were adopted to provide sufficient tension to the line and guarantee the line grip where the incremental encoder is positioned to avoiding sliding and false signals.

**Step 2:** Data receiving. Once the movements responsible for generating the signal occur, the microcontroller is set to count the pulses on the square wave generated by the incremental encoder at a resolution of 50ms.

**Step 3:** Mathematical treatment of the data. The number of pulses collected determines the real data of velocity by using the value of the diameter of the pulley and the pulses generated.

**Step 4:** Serial communication. The loop of a computer program is responsible for reading each value of velocity and passes this to the microcontroller to send to the serial communication port. The values are then available to be read using MATLAB (MathWorks 2013) which is responsible for a real-time plot.

**Step 5:** Real-time plot. The serial port provides Matlab with the data which it saves it on the computer flash memory where the data can be read at any time. With the objective of
providing a real-time plot, the data was received from the microcontroller at 50ms increments, and the plot provide in real time. An algorithm is responsible to provide velocity real-time graphs on the screen to be used by the coach.

Step 6: Data saving. For further analysis, all collected data are stored as matrix elements in a text file associated with the swimmer’s name the stroke, the time and the velocity iparameter.

Swim velocity profile identification

Many identification techniques can be used to provide information about the athletes’ performance. This section presents a Radial Basis Function Neural Network (RBF-NN) improved by the stochastic Generalised Extremal Optimisation (GEO) method to provide a fast convergence in the velocity identification procedures.

Radial Basis Function Neural Network (RBF-NN)

Inspired by the biological nervous systems, a neural network is a highly interconnected processing elements (neurons) working in unison to solve a specific problem. The particular RBF-NN is considered a three-layered network, where the input nodes provide the input values to the internal nodes that formulate the hidden layer. In RBF-NN, weights are not considered between the layers. The nonlinear responses of the hidden nodes are weighted in order to calculate the final outputs of the network in the output layer (Poulos et al. 2010).

To adjust the RBF-NN to provide desirable results some parameters must be set, these parameters are the centres, the widths, and the output weights. The structure of the RBF-NN is presented in Figure 2 and illustrates the relationship between the m-dimensional input vector $x \in \mathbb{R}^m$ and the n-dimensional output vector $y \in \mathbb{R}^n$, $f(x) \rightarrow y$. Additionally, Figure 3 shows the connections between the layers, the basic functions $\phi_i$ and the weights $w_{ik}$.

![Figure 2 Structure of the RBF-NN (Coelho et al. 2013)](image)

According to Karayiannis and Mi (1997), learning can be seen as a function approximation problem and it is equivalent to finding a surface in a multidimensional space that provides the best fit to the training data.

The nodes within each layer are fully connected to the previous layer. The input nodes are directly connected to the hidden layer neurons. There have been a number of popular choices for the basic function at the hidden layer of RBF-NNs. The most common choice is a Gaussian function. In this work, the output of the $j$-the hidden neuron using the symmetrical Gaussian function can be written as (Coelho et al. 2009):

$$y_j = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x_j-c)^2}{2\sigma^2}}$$
\[
\phi_j(x) = \exp\left(-\frac{\|x - \mu_j\|^2}{\sigma_j^2}\right)
\]  \hspace{1cm} (1)

where \( x = (x_1, x_2, \ldots, x_m)^T \) is the input vector, \( m \), the number of the hidden layer neurons, \( \mu_j \), the center vector, \( \sigma_j \) the radius width of the \( j \)-th hidden node and \( \| \cdot \| \) is a norm on the input space.

The output layer represents the outputs of the RBF-NN and each output node is a linear combination of the \( k \) radial basis functions of hidden nodes:

\[
y_i = \sum_{j=1}^{k} w_{ij} \cdot \phi_j(x)
\]  \hspace{1cm} (2)

where \( w_{ij} \) is the synaptic weight connecting hidden neuron \( j \) to output neuron \( k \).

**Generalised Extremal Optimisation (GEO)**

As both centres and the width of RBF-NN must be set adequately to provide reasonable results, this work includes an optimisation technique called Generalised Extremal Optimisation (GEO) to realise the dynamic of the width and its influence on the identification procedure. The main objective is to provide the best curve fitting as possible. The centres have been configured by using the expectation-maximisation (EM) clustering method (Dempster et al. 1977).

According to Sousa, et al. (2004), Generalised Extremal Optimisation is an optimisation method capable to tackle optimisation problems with complex design spaces. GEO extends the Extremal Optimisation (EO) method, proposed by Bak and Sneppen (1993), in a way that it can be simply applied to many optimal design problems. Another characteristic of the GEO is that it has only one free parameter to be set, differently to other popular stochastic algorithms that have at least three parameters. More information about the GEO can be found in the work proposed by Sousa et al. (2004). The maximisation problem presented in this paper is calculated by using the expression of \( R^2 \) presented in Equation 3. In this equation, \( N_s \) is the number of samples, \( y(t) \), the output of the time series, \( \hat{y}(t) \), the estimated output by the RBF-NN and, \( \bar{y} \), the mean value of the system’s output. \( R^2 \) equal to 1.0 (estimation or validation phases) indicates that the model’s accurate approach to the system’s measured data. According to Schaible et al. (1997), \( R^2 \) values between 0.9 and 1.0 are considered sufficient for many applications in identification and forecasting fields.

\[
R^2 = 1 - \frac{\sum_{t=1}^{N_s} [y(t) - \hat{y}(t)]^2}{\sum_{t=1}^{N_s} [y(t) - \bar{y}]^2}
\]  \hspace{1cm} (3)

**Prototype tests and results**

This section presents the test procedures and results obtained by using the prototype described in Section 2 of this work. It was considered a single test and real-time data acquisition of a Brazilian elite male swimmer performing the crawl stroke. The test was performed in a 25 meters swimming pool. The prototype was positioned above the start block as illustrated in Figure 3. The crawl stroke velocity analysis has been selected due to its non-linear time series behaviour providing challenging data for the identification technique.
A total 280 samples have been used in this study where 210 and 70 samples have been selected for the estimation and the validation phases, respectively. As presented before, GEO has only one parameter to be set, the population size was set to 20 and 500 has been selected for the maximum iterations number. Figure 4 (a) presents the best results for the velocity estimation phase obtained by RBF-NN. The error is available in Figure 4(b).

In this design, the pseudo-inverse was employed in the RBF-NN output layer and for its input three delayed samples have been used. A multiple correlation coefficient higher than 0.9 for both estimation and validation phases was obtained using the proposed RBF-NN (Table 1). However, additional tests have been performed and $R^2$ values between 0.90 and 0.98 have been obtained for more linear swim strokes as breaststroke and butterfly. Backstroke results provided similar results as the crawl stroke.

Table 1  Multiple correlation coefficient $R^2$ for both estimation and validation phases

<table>
<thead>
<tr>
<th>Number of Gaussian functions</th>
<th>Estimation phase</th>
<th>Validation phase</th>
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<tr>
<td>2</td>
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<td>0.000000</td>
</tr>
<tr>
<td>3</td>
<td>0.153205</td>
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<td>0.814550</td>
</tr>
<tr>
<td>9</td>
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<tr>
<td>10</td>
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</tr>
<tr>
<td>11</td>
<td><strong>0.902105</strong></td>
<td><strong>0.900993</strong></td>
</tr>
<tr>
<td>12</td>
<td>0.901095</td>
<td>0.898873</td>
</tr>
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</table>
An identification procedure by using the velocity data of a Brazilian elite male swimmer in the crawl stroke have been obtained in a 25 meters test and a black-box model, capable of providing the athlete velocity was found and validated. The expectation-maximisation clustering method was used to tune the Gaussian functions centres and Generalised Extremal Optimisation method was adopted to optimise the Gaussian functions width and to reduce the number of empirical variables of the Radial Basis Function Neural Network. Identification results report the possibility of enhancing the performance of athletes in terms of using their velocity parameter by comparing their velocity profile models in terms of a mean, a maximum and a minimum value. Future works are directed to evaluate new identification techniques in swimming time series forecasting, to improve the prototype precision and increase the number of samples per second and enhance the software performance by including video synchronisation.

References


Exploring beliefs about swimming among children and caregivers: a qualitative analysis

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Introduction

Beliefs about what swimming really is may influence expectations in the learning situation. And expectations often influence motivation. While aquatic experts ‘may’ agree on what should be taught, there may be disparity between what the ‘providers’ and the ‘clients’ believe. This suggests a need to inform both children and caregivers about why certain elements are important and need to be included, in addition to simply teaching them. Potentially, this information, if integrated in a creative way, will broaden the scope of teaching, broaden the horizons and even expectations of both children and caregivers, and in general, enrich the learning experience. Finally, teaching will better meet the needs of the drowning prevention intention when essential skills are included and their value becomes known to the learner. This is part of the knowledge package which is also our responsibility to deliver along with skills.

All aquatic professionals and even less experienced instructors, when focusing on skills diversely called confidence, adaptation, or most appropriate, ‘readiness’ skills (1), have heard the common question from caregivers, ‘when are they going to learn to swim’? This virtually always means, when will they learn strokes? And interestingly, if one is working on a specific stroke, even this may not be considered swimming in some parts of the world and we get the same question. We have seen that this is often a reference to breaststroke or to front crawl, where one is considered swimming, but the other not, or vice versa. Historically, breaststroke is favored in Europe and front crawl in North America, Australia and New Zealand. And other important strokes (e.g. side stroke) let alone such


important skills as treading water, survival float, surface diving, etc are even less recognised by caregivers.

Another question or perhaps an unfortunate ‘attitude’ is reflected by the comment from caregivers that ‘my child is very adapted to the water and is now ready to learn to swim’. This tells us that the caregiver a) does not consider learning the foundational readiness skills part of learning to swim and b) that they focus on propulsion (i.e. stroking) in their mental picture of what swimming really is.

Several studies within the international project ‘Can You Swim?’ have now shown that both young adults and children, are not particularly good at accurately predicting what they really can do in the water. They perceive their skills and knowledge to be something different than what they really are (2). In New Zealand, Australia, Norway and Japan, young adult males perceived their skill to be better than it really was and thus might be exposed to greater risk. In both Norway and Portugal, children were also unable to accurately predict what they could do in the water (3,4). Especially young adult males also perceived their risk as lower than females, though they were in reality, no better in their skills. This suggests that knowledge of why certain skills are essential and a better understanding of how far that person has come in mastering these skills, is not only a necessary part of teaching, but also our responsibility to deliver. This is part of the knowledge package within water competence. And it has becoming increasingly accepted that the minimum teaching package which is our responsibility to deliver, is a water competence package, i.e. skills plus attitudes, values, knowledge, judgment and safe behaviour (5). It is never acceptable to teach skills alone though we know that it is unfortunately all too often done.

**Aims**

This study aimed to explore a) the beliefs of children and caregivers about what swimming really is and b) their beliefs about the relative risk of swimming outdoors in waves. Specifically, we aimed to explore:

1. The total number of responses to each of the above questions
2. The number of ‘different’ responses
3. The number of responses per subject
4. The responses of first choice
5. The clusters formed when very similar responses are grouped together

**Methods**

This was part of a larger study which examined the performance decrement when comparing swimming in quiet water to swimming in a simulated outdoor environment in a wave pool (3). The wave condition is pictured below in Fig. 1. The ball in the background has hydraulically controlled moving parts which, when moving cause the ball to move up and down, thus causing the waves. Wave height is adjustable at four settings. Wind, rain and failing light can also be simulated.
Children (N= 101, age 11 yrs) and their caregivers (N= 77) were asked to express in writing, a) their beliefs about what swimming is and b) about the difference between swimming in quiet water and outdoors in waves. All responses were individually recorded. The analysis examined a) the total number and frequency of responses, b) the number of different responses, c) the number of responses per subject, d) the frequency of first choices, e) the clusters created when all responses were reduced to similar elements.

Subjective expert judgment was used to identify individual elements in each response. For example, the statement ‘I have to keep myself afloat and not drown. I have to be able to swim a certain distance’ was considered to include three different elements. All were individually recorded and assigned to that respondent.

This protocol was followed for both of the above questions and also for both children and caregivers.

**Results**

**What is swimming?**

Few identified more than 2-3 of the 10-12 elements normally recommended by aquatic experts as essential content when teaching swimming (6). The caregivers had a more nuanced view of what swimming is than the children, with 2.45 (± SD 0.45) responses per subject vs 1.64 (± SD 0.59) responses for the children. Among 101 children, 164 responses were recorded regarding beliefs about swimming, 31 different responses, and 6 clusters of similar responses were identified. Among 77 caregivers, 181 responses were recorded, 37 different responses, and 5 clusters were identified. The most common responses among children about what swimming is, were: propulsion (28%), to be safe (24%), to stay afloat (23%), not to drown (21%). Among caregivers, the most common were: propulsion (53%), to stay afloat (24%).
When comparing children and caregivers on the clusters of their beliefs about what swimming is, we see in Fig. 3 above that the most dramatic differences were a) nearly twice as many caregivers were primarily concerned with propulsion, i.e. stroking, b) children were more concerned about being safe, c) only the children mentioned not drowning (21%), d) only the caregivers mentioned movement underwater. Finally, both children and caregivers were nearly unconcerned about breathing, the skill set most experts consider most important of all (6).

**Relative risk outdoors**

Regarding the relative risk of swimming outdoors in waves, 116 responses were recorded among the children, with 21 different responses, and 9 clusters were identified. Among the caregivers 141 responses were recorded, with 34 different responses and 7 clusters were identified. The most common responses regarding relative risk among children were a) waves are more dangerous (48%), b) it is safer indoors (19%). These are two sides of the same issue. The most common responses regarding relative risk among caregivers were, a) waves are more dangerous (31%), b) feeling of loss of control e.g. waves, currents, etc. are unpredictable (22%), c) there are currents outdoors (13%) and d) more difficult to breathe in waves (3%). When comparing the children with the caregivers, the most dramatic differences were, a) far more children than caregivers felt that waves were more dangerous, 48% vs 31%, and that the pool was safer (19% vs 5%), b) only the caregivers were concerned about losing control, and this was quite prevalent (22%), c) only the children were concerned about the depth of the water (6%).
Finally, only a few children and caregivers were concerned about breathing and few mentioned colder water (a serious survival problem – even moderate temperatures can produce cold shock or hypothermia, (7).

**First choices**

It may be that a respondent’s first choice, i.e. what first comes to their mind when answering these questions, may be more important than additional responses. This is of course, only speculation.

Analysis of first choices should uncover information lost if any, when examining all responses, if there are differences.

When analysing the first choices, the clusters identified earlier – did not change. Identifying these clusters was deemed to be the most important result. There were however, a few differences between examining all responses compared to only first choices, which are worthy of mention. Fig. 7 above shows that only 15% first chose propulsion compared to the 28% when including all responses, i.e. propulsion along with other elements. This might mean that children were in fact, less obsessed with propulsion that the 28% suggests. No change was seen among the caregivers where it remained at just over 50%. Second, staying afloat increased (24% - 33%) among adults while remaining at the same level among children. And being safe in the water was chosen first by 24% of adults while when all responses were considered it was only 14%, with little change among children.

Regarding relative risk there were also only a few noteworthy changes when analysing first choices. The majority of responses voicing concern for the danger of waves remained unchanged.
That a pool was considered safer also comes as no surprise. The caregivers were considerably more concerned about currents, possibly reflecting greater knowledge. Once again, as when considering all responses, only the children were concerned about depth and only caregivers expressed concern for loss of control. It is also noteworthy that so few were concerned about breathing, colder water, and distance from shore.

**Conclusions**

The beliefs of both children and parents were less specific and different from expert opinion. Part of the teaching process should be to inform learners about the need for and importance of certain essential items. This may broaden expectations and improve motivation. The results also show that both children and caregivers were mostly concerned with propulsion although the caregivers seem to be considerably more concerned with propulsion than the children. Not only were there differences in beliefs among individuals but also between children and caregivers. And most evident were the differences between these two groups and aquatic experts who usually consider 10-12 different items as essential foundational items in a definition of swimming. Most notably, breath control or any reference to breathing were very rare although aquatic experts consider this aspect the most important of all. And direct reference to floating was also not so common. Changing direction and position were not mentioned at all.

Both children and caregivers felt that it is more dangerous to swim in open water in waves but the reasons given varied. Children expressed considerably more concern about the danger of waves. We can speculate that at 10-11 years of age, they have less experience swimming in open water. And perhaps this new generation is even more over protected and spoiled by warm, modern swimming pools.

Analysis of first choices does not, at this stage seem to indicate that any vital information is lost by focusing on all responses and not assuming that the first choice is necessarily most important.

**References**


**Balanced progress: optimal protection in a survival context**

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**Keywords:** survival, balanced progress, optimal protection

**Introduction**

In any drowning episode, some weak or missing skill is usually the factor which triggers the emergency. Perhaps other weak skills (usually skills linked to the first) in the person’s skill profile then add to the episode. Finally the foundation collapses and the ‘episode’ becomes a drowning. Identifying these ‘causes’ of drowning tells us what should be learned, i.e. what the content of any aquatic educational program should include. In depth interviews of survivors of drowning have identified many of these ‘weakest links’ (1).

![Figure 1](Image)

**Figure 1** Causes of drowning and what should be taught

![Figure 2](Image)

**Figure 2** Unbalanced vs balanced progress
At any given stage of aquatic skill development, the optimal level of protection is achieved when all essential elements are evenly developed. Elsewhere, the principles of such development have been described as a) equally proficient on front and back, b) equally proficient underwater and at the surface, c) possession of a well balanced and all around aquatic skill base (1,2). Common examples of persons without balanced development are those who are moderately skilful on the front but very weak on the back (or vice versa), or moderately skilful at the surface but very weak just a few centimeters below the surface. These persons are more prone to get into difficulty, especially when confronted with an emergency situation which demands the skill which is their ‘weak link’. It does not help to be good on the front if you find yourself on your back, unable to roll over or to swim on the back—or at the surface when you find yourself well under water. The arrows above in Fig. 2 represent individual essential skills. On the left, some are poorly developed while others are well developed. On the right, all are roughly equally well developed.

There is an historical tradition of balanced, all-around aquatic skill development, embodied in the historical concept in English speaking cultures, of ‘watermanship’, unfortunately an idea all but lost today. One possessing this quality, it was understood, had mastered control of the aquatic environment, including their own breath control and buoyancy control. More correctly stated, rather than controlling the environment, they had learned to cooperate with the aquatic environment, adjusting the physical characteristics of the human body to those of water, i.e. cooperating with the laws of nature (2). This ‘water man’ or ‘water woman’ could move with ease in the water, in any of many ways, in any direction, in any position, like a bird in flight suspended in the air, as we are suspended in water while swimming (3). In the late nineteenth and early twentieth centuries (especially in Britain), some such persons actually earned their living by demonstrating for paying spectators, positions and movements which the aquatically uneducated audience had previously thought impossible (4).

Among these traditions of a century ago, still remembered by those previous generations still surviving and who learned in that tradition, were the notions that whether one can swim 10 meters or a 10,000 meters on the front, they should be able to do the same on the back. If one can swim for one minute or 100 minutes, one should be able to stop and rest for roughly the same amount of time. If one can surface dive to one body length of depth, one should be able to swim 2-3 body lengths underwater. More broadly phrased, ‘one who can swim can cope with an unexpected fall into deep water’, i.e. possesses a broad and balanced repertoire of aquatic skills (2,5,6).

Currently, few aquatic educational programs focus on this kind of balance. In fact, it is rarely discussed and just as rarely mentioned in the modern literature. In fact, some organisations specifically dictate against balanced progress. A common northern European tradition considers proficiency on the back as less important than on the front and many organisations support a wide variety of awards which demand 3-4 times as great a distance to be covered on the front as on the back. For example, among the criteria for certain common awards, the candidate must swim 200 meters, ‘of which at least 50 meters must be on the back’. This obviously suggests that swimming on the front is at least three times more important than on the back. This is simply incorrect and highly regrettable.

To what extent individual instructors contribute to this dilemma is yet un-quantified, but common observations include the instructor who tries to teach arm or leg movements to the child who refuses to put the head in the water and/or cannot yet float (typical of those enthralled with the use of artificial flotation). We have all seen the instructor who tries to teach gliding before the pupil can float. Some instructors cultivate a high level of proficiency on the front before even introducing floating, gliding or stroking on the back, or vice versa. Some are enchanted with a given stroke/style and neglect others, not understanding that each of perhaps a dozen strokes are equally important, that each has its own unique contribution.
**Methods**

A conceptual model is presented on the premise that the weakest element in a person’s skill profile is the one most likely to trigger an emergency situation in the water, i.e. a potential drowning. The chain is only as strong as the weakest link. From a previous study, in depth interviews with drowning survivors have uncovered typical weaknesses in skill development (1).

**Results**

When skill development is uneven, weak spots or holes are left in the foundation. Because foundational skills are weak or missing, the next row of blocks (skills) is weaker. Pressure grows as the wall gets higher. One missing block leads to another. A fault line develops. Finally, the wall collapses. A weak or missing essential survival skill has triggered a drowning episode. Unfortunately, the inexperienced instructor may not be aware of certain essential (foundational) blocks in the wall and inadvertently creates holes (missing blocks), skipping some essential skill. Here a common observation is the underestimation of the need for extensive development of breathing skills. The experienced instructor on the other hand, usually identifies difficulty at any stage, as somehow related to previous skills (e.g. in a lower level in the foundation) which are missing or poorly developed. One stops the building of the next row of blocks until the hole is filled in the row below (see Fig 3).

![Missing blocks in the foundation](image)

In Fig. 3 we might imagine that the first row of blocks represents breathing skills while the second row are buoyancy (floating) skills, the third gliding and the fourth propulsion. Failing to complete the first row compounds itself in weakness of the second row and so on. The inexperienced instructor continues to build the wall higher, not seeing the weaknesses as they appear. In fact, this instructor may actually contribute to creating a weak swimmer who is more prone to getting into difficulty.

![A hypothetical skill profile](image)
Fig. 4 represents a hypothetical skill profile which might represent the skills of a given individual at a given point in time. On the X axis, the individual skills are identified (A, B etc). Note the arrow indicating that this list is not complete. On the Y axis, the level of efficiency of the skill is plotted. The optimal situation, the goal of teaching, is that all of the essential skills should arrive simultaneously on the same horizontal level. Weaknesses are easily identified in this way and can be promptly attended to. Such a curve can also be generated which represents mean values of a group (e.g. a school class). The curve of any given individual could be superimposed on a group curve to indicate how this person compares to the group. Another application of mean profile values would be to compare two groups, e.g. the boys and the girls in the class named above. A curve representing mean values for a group also identifies weaknesses (for the group in general) and perhaps can also serve as an evaluation of teaching.

As can be seen in Fig. 5, several qualities have been quantified in their progression and these compared with one another. The list is but an example, not meant to be complete (though most of the more important and obviously necessary skills are included). A learner who can swim 25 meters should also be able to do half of that distance on the front, half on the back (i.e. two strokes — one on the back and one on the front), should be able to surface dive to 1.5-2.0 meters, swim 2-3 body lengths under water, stop and rest for 30 seconds, swim lightly clothed, jump into deep water, recover to the surface and level off, roll over, turn, and finally, exit in a safe manner. All of these skills should progress in a balanced way. As one skill improves, the others should keep pace.

**Conclusions**

Water safety education must strive for balanced development of essential protective skills. In an informal, non-organised setting, children normally learn several skills at more or less the same time. This should make it easy to introduce several skills at virtually the same time, as a routine practice. An obvious pair is floating and standing. One virtually cannot exist without the other. They must be learned at the same time. When focusing on contrast pairs e.g. floating on the front and floating on the back, introducing these in parallel (7) not only stimulates balanced progress, it allows children to choose, to learn according to their own needs. Though most will learn to float on the front first, some naturally learn on the back first (8). Fewer are ‘left behind’. A reflectively designed progression has a number of points at which paired skills are introduced. These are the perfect opportunity to introduce two skills at the same time — e.g. floating on front and back (as named above), rolling from front to back and back to front, gliding on front and back, kicking on front and back, pulling on front and back, beginner stroking on front and back, turning left and right, on front and back.

The argument for an all around skill development is simply that one cannot predict, in advance, what skills will be required to meet which emergency situation. Returning to the notion that a drowning episode can unfold in many different ways, one needs to be prepared for a variety of possibilities. A
fall from height can result in the victim being on front or back, perhaps well under water, injured on landing, wearing full clothing, breath knocked out upon landing, and other unexpected circumstances beyond prediction. The only way to tackle this dilemma is to prepare in advance, in a proactive attempt to cover all or at least many possible scenarios.

Finally, if and when possible, every attempt should be made to provide a balance between the pool or quiet water experience and the open water experience. We know that by far most drowning occurs in open water. We also know that for many who have learned in a pool, the transition is too great and leads to a negative outcome. This transition needs to be introduced at carefully calculated and developmentally sound points in time.

If we succeed in covering the survival needs with this balanced, all – around development approach, we have fortunately also established the optimal sound foundation skills for further skill development. Though not broadly understood, the same skills which offer protection also offer the stepping stones to further skill learning. These skills are thus termed ‘foundational skills’ (2).

If we are able to identify which missing or weak skills trigger typical drowning episodes, we have then identified essential skills in the content of any teaching program, i.e. what should be learned (1). As depicted in Fig. 1 above, this in turn leads us to how instructors need to be trained in order to teach these essential skill items. Having identified essential skills, we then proceed to construct a progression, the pedagogical tool of teaching, careful to retain the broad, balanced base throughout, as skill increases.

References
The concepts, ‘can swim’ and ‘water competence’—their relationship: a conceptual model

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\[1,2,3\]

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**Keywords:** swimming, water competence, definitions

**Introduction**

Experience suggests that many conduct research on swimming or pontificate over the educational aspects of swimming without reflecting on what swimming really is. Partly because many stakeholders have failed to conduct this internal reflection, a concise definition of what swimming really is has yet to be broadly adopted. What is taught varies dramatically from one place or organisation to another. Many people believe that swimming is what is done with the arms and legs in the water, i.e. stroking. But swimming is much more! All *around* aquatic movement development is required not only to best prevent drowning but also to build a foundation for further skill development as well as to provide aesthetic and emotional pleasure. It is not broadly recognised that by their very nature, the same skills which protect are also those which build the foundation for further progress. Langendorfer and Bruya appropriately call these foundational skills (1). In addition to this broad skill base we must also add attitudes, values, knowledge and judgement, hopefully leading to informed safe behaviour, increasing the protective value. We now call this larger package, i.e. skills plus the above named affective and cognitive qualities – ‘water competence’.

The element within which swimming takes place is a three dimensional space, in a fluid in which the body is suspended, just as a bird is suspended in flight. Movement within this space is also three dimensional. The bird can go up or down, left or right, forward or backward (humming birds can fly backwards, like a helicopter), and rotate in any direction performing brilliant acrobatics. This immediately tells us that only part of swimming takes place on the two dimensional surface. In fact, when at the surface, three dimensional movement is impossible. You cannot go up! Going up depends on having gone down first (ie only when completely submerged is real three dimensional freedom of movement possible). And this is not possible without breath control and buoyancy control, fundamental building blocks of swimming and of the teaching of swimming. We see already that swimming is not ONLY propulsion (stroking). The qualities described below will contribute to real freedom of movement in an aquatic environment. They must be included in our teaching. *They can save a life in an emergency.*

So, if swimming is not stroking, what is it? Prof. H.T.A. Whiting pointed us in the right direction when he described a swimmer as one who can cope with an unexpected and involuntary submersion (2). In other words, one who possesses a so broad reperatoir of aquatic movement skills and other qualities, that many challenges can be overcome. The form which a drowning episode can take is influenced by many factors and can unfold in many ways. Many solutions are thus required to solve many potential scenarios. The survival element lies in being proactive, preparing in advance for a wide variety of possible scenarios, not the least of which is the open water experience, which is where most drowning occurs. The idea that the transition for persons who have learned in quiet, warm water, to open water, is too great for many, is growing in acceptance. In fact, as you will see, we suggest that part of the definition of being able to swim, is to also be able to perform the recommended skills both while clothed and in open water (3).

In 1995, Langendorfer and Bruya coined the phrase ‘water competence’ (1), adding to well balanced all around swimming skill, both cognitive and affective qualities. Moran (4) has defined water competence in a drowning prevention context as ‘the sum of all personal aquatic movements that help prevent drowning as well as the associated water safety knowledge, attitudes, values, judgment and behaviors that facilitate safety in, on, and around the water’. All around swimming skill is the
nucleus or core of ‘water competence’. However, even if sufficient skill is present, lack of knowledge of local hazards, for example, can lead to a fatal decision.

A definition of swimming is necessary to advise teachers, instructors and program planners about content, i.e. what should be taught. Appropriate content not only defines swimming, it has protective value in a drowning prevention context. Furthermore, it is contended that no other goal for the teaching of swimming than the drowning prevention intention, is morally acceptable as the primary goal.

The 2006 edition of the Handbook on Drowning (5), Chap. 3.8, ‘Swimming ability, water safety education and drowning prevention’—identified research needs and authors recommendations including:

- ‘Continued development and dissemination of a concise definition of swimming ability (skill) as it relates to drowning prevention’.
- ‘That swimming ability (skill) be promoted as a necessary component of water competence but with the understanding that swimming ability (skill) alone is (often) not sufficient to prevent drowning’.

Thus the aim of this article is to explore what swimming really is, to show that swimming is more than propulsion, more than stroking. We support a philosophy which defines swimming to include those qualities which are especially survival oriented. This philosophy has existed for ages but we wish to reinforce it and hopefully present it in a way that may be new for you.

We will also define the concept of water competence, which adds, attitudes, values, knowledge, judgement and informed behaviour—to swimming skill, increasing the level of protection. And when we look at how the above can be organised and risk can be reduced or even eliminated by collective action of the society including governmental regulations and policy change, we discuss the inclusive concept of ‘water safety’.

**Methods**

Four sources of data have been used to construct a definition of swimming, i.e., of ‘CAN SWIM’: 1) a review of course content at the beginning level, of 25 well known organisations, 2) in depth interviews with drowning survivors, 3) observation of simulated drowning episodes, 4) theoretical movement analysis (3). Skill alone is often not enough to prevent drowning. Water competence which includes skill, was defined by polling expert opinion. Elements which were commonly repeated in the above data sources were considered essential elements in the definition of swimming. Affective and cognitive elements most often named by experts were considered essential elements in the definition of water competence.

The assumption is made that all – around aquatic skill development is most protective, The relationship between swimming skill and water competence was devised as a conceptual model. Collective societal action to promote these two concepts is described as water safety.

**Results**

**Swimming skill**

The resulting definition of swimming skill focuses on essential protective skill elements in an all-around aquatic skill development. Each of these has a protective value of its own as well as collective value when integrated with each other. The elements which were commonly repeated in the original sources of data were: control of a) breathing, b) buoyancy, c) posture, d) position, e) rotation, f) propulsion, together with coordination and agility—all of these both clothed and in open water. See Fig. 1 below. Fig. 2 translates these movement qualities to specific skills. Both of these graphic presentations describe a recommended definition of what swimming really is.
Swimming skill is essential although it is recognised that it often is not enough in itself, to prevent drowning. It is however, the foundation, the core, and although prudent behavior can save a life, there is no substitute for swimming skill as the foundation. The figures below show how swimming skill can be described as including the qualities listed above.

Together the above elements provide a very sound foundation. They include most of what are usually described as survival skills (survival floating, sculling, treading water, surface diving and underwater swimming, swimming with clothes, etc). Other specific skills can then easily be added; removing or putting on clothes, using clothing as buoyant aids, use of a PFD, etc.

![Diagram of swimming skill elements]

**Figure 1 Essential movement qualities**  **Figure 2 Translation to specific skills**

Skill itself i.e. what it means to be able to swim, can be and is here defined relative to drowning prevention. You will see below in describing water competence, that swimming skill is the core of water competence.

In examining programs of well known organisations, three ideas were repeated sufficiently often that we feel they deserve to be considered principles.

- The learner should be equally comfortable and proficient under the water and at the surface.
- The learner should be equally comfortable and proficient on the back and on the front.
- The learner should develop a balanced, all-around movement repertoire (as described above).

From the above considerations, we suggest the following as a definition of swimming.

1. Entry (i.e., jump or dive) into deep water
2. Upon submersion, regain surface, level off and swim
3. Surface dive and swim underwater with comfort
4. Able to perform at least two rudimentary strokes, one on the front, one on the back
5. Breathe in a relaxed way and in a manner integrated efficiently with the task at hand.
6. Change body position in the water (i.e., roll over from front to back and back to front)
7. Change direction of travel (i.e., turn left and right—both on front and back)
8. Stop and rest with minimal movement; (N.B. no movement is necessary for prepubescent children or women, all of whom are anatomically capable of floating)
9. Exit safely at an appropriate place
10. All of the above while clothed and in open water

**Water competence**

Water competence is defined to include skill plus the cognitive and affective competencies which provide additional protection, i.e. attitudes, knowledge, judgement, values and behavior. The conceptual model of the relationship between swimming skill and water competence places skill as the core of water competence with the affective and cognitive qualities added for increased protective value (see Figs. 3 & 4 below). In saying ‘added’ we do not mean as an afterthought and after teaching skill. The optimal approach is an integration of all of the above. For example, regarding healthy attitudes of respect for the powers of nature (water), the approach of the instructor and her/his own private attitudes will affect the learners. As a teacher, your private attitudes are transparent. You have the power to use it for a positive result, transferring your beliefs to the learners. Values will include e.g. the health aspect, swimming being an excellent form of personal exercise. Values will also include the emotional and aesthetic aspects of aquatic activities.

![Figure 3 Swimming skill as the core](image1)

![Figure 4 Adding cognitive and affective qualities](image2)

Knowledge can be approached in a wide variety of ways and focusing on a variety of necessary information. One of the most critical is knowledge of local hazards. In open water in the vicinity, there may be rip currents, drop offs, submerged hazards (the wreck of a car or boat), rapidly shifting water and weather conditions, extreme tidal conditions, rapidly changing temperature, predators, infectious microbes. Knowledge of ones own real skill level is also important and can only be formed via developmentally appropriate evaluation as a routine part of instruction. Accurate knowledge of ones own competency level should help to avoid underestimation of risk (6). Judgment can be instilled by role playing in constructing scenarios that challenge and help to develop the learners decision making skills. Safe behavior is something we practice in all contact with learners. We should also inform them of safe practice in other situations and describe both potential risk and discuss real episodes (e.g. from newspaper clippings), attempting to instill a kind of risk assessment mentality (7).

It is our responsibility to teach all of the above, i.e. the minimum teaching package must be a water competence package. While skill is often taught alone, this is seen as indefensible. Skill teaching must always be accompanied by the teaching of attitudes, values, knowledge, judgment and safe behaviour. It is never acceptable to teach skill alone.

**Water safety**

Water safety is defined in this conceptual model as all collective efforts of any society to promote all aspects of drowning prevention, be it local, provincial, national or international. Water safety education might include the following: a) provision of swimming and water competence instruction, b) water safety awareness taught in the school classroom, c) awareness campaigns for the general public, d) the training of swimming and water safety instructors and lifeguards. Community action might include eliminating certain risk by fencing off dangerous open water areas making them unavailable. Political action could include creating or enforcing existing regulation of fencing for
private water facilities (both recreational – e.g. home pools, and industrial facilities including open water processing).

Political action and policy change might include requiring and/or providing specific competency training for lifeguards, swimming instructors and school teachers involved in teaching swimming. Internal training within organisations could include creating opportunities for children and youth for aquatic activities or quality control where these already exist. Communities often cooperate with both public agencies such as police and fire brigade and private or semi-private non-profit organisations like Scouts, Red Cross, YMCA and many others. Civic organisations such as Lions Club, Rotary or Kiwanis are often involved in community wide activities. There are literally dozens of ways a community can make itself ‘water safe’.

![Figure 5 Water safety includes skill and water competence](image1)

![Figure 6 Adding collective, societal action](image2)

**Conclusions**

Swimming skill is most often the entry point at which we meet children, youth and adults wishing to learn or to improve their skills in some aquatic activity. We have in some ways, a captive audience. Though they come to learn skills, they will get more in the bargain. The necessary skill profile is an all-around development of a broad skill base specifically including protective skills. The contents of such a skill profile and the contents of any educational effort to create such a skill profile among all persons, are described above.

Swimming skill is also the core of water competence. To this core is then added all cognitive and affective competencies which increase the protective value on, in and around the water. The minimal teaching package which we should deliver, is a water competence package. It is also our responsibility to include these affective and cognitive qualities integrated with any skill instruction.

Finally, any and all activities collectively designed to prevent drowning, including both skill and water competence education, are designated ‘water safety’.

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