Pedro Morouço, Hideki Takagi e Ricardo J. Fernandes

Sport Science:
Current and Future Trends for Performance Optimization

Escola Superior de Educação
e Ciências Sociais — Instituto Politécnico de Leiria

Centro para o Desenvolvimento Rápido
e Sustentado do Produto

Datasheet

Title
Sport Science: Current and Future Trends for Performance Optimization

Editors
Pedro Morouço
Hideki Takagi
Ricardo J. Fernandes

Edition
Escola Superior de Educação e Ciências Sociais — Instituto Politécnico de Leiria
Centro para o Desenvolvimento Rápido e Sustentado do Produto

Graphics and Composition
Rui Lobo

ISBN
978-989-8797-19-3

Legal Deposit
xxxx

Index

Preface

To improve athletes' performance, a massive amount of effort by themselves and coaches is obviously essential. However, one cannot ignore the impact of that science has nowadays on their performance improvement. In swimming, for example, swimsuits developed based on state-of-the-art knowledge in fluid dynamics between 2007 and 2009 (which were all banned due to changes in FINA rules and regulations in 2009) allowed many swimmers to break world records, some of which are still unbroken in 2018.

Methods used to assess athletes' physical and technical performances are developing every single day, and new training theories are provided with remarkable speed. Ideally, it would be of great help for athletes if coaches knew all updated methods and knowledge to provide the most effective training processes. However, this is quite difficult in reality and there are always gaps between theories and practices in sports. Athletes/coaches and scientists have been trying to fill the gaps by working together, but just conducting collaborative work would not solve the issue because the goals of scientists and athletes/coaches are, in many cases, quite different. For scientists, the goal is to answer 'why' good athletes can achieve great performances with objective evidence. On the other hand, athletes and coaches want to know 'how' they can enhance the performance and, ultimately, objectiveness and evidence are not essential for them.

Then, how can we fill the gaps? One possible answer is to have 'interpreters' or 'translators' between scientists and athletes/coaches, such as performance analysts or scientists who also have long coaching experience. It is also important for scientists not to only focus on studies with statistical data, but also to publish many scientific case reports for readers to obtain ideas they can directly apply to the training.

This book is full of exciting research topics provided by leading 'interpreters' in sports and we hope it will be a bridge between theories and practices. It includes studies on individual, closed and cyclic sports, but also on team sports and individual sports highly dependent on the opponent behaviour (as tennis and combat sports). This is very relevant as, nevertheless (e.g.) running and cycling have a relevant and pioneer historical background in research, other sports are also growing in quantity and quality in terms of studies. We also aimed to achieve a balance between hard and soft sciences approach in this book, providing both experimental and conceptual studies.

We want to acknowledge the authors that made contribute with their intellectual property to this book and the reviewers for giving their expert comments. We hope that it be useful for the Sports Science related community, helping consolidating existent knowledge but also encouraging innovation and creativity, pleasing the readers with its contents.

Pedro Morouço, Hideki Takagi, Ricardo J. Fernandes

Lost in translation – getting your sport science research message across

David B. Pyne[1,2] **and Naroa Etxebarria**[1]

Introduction

The sport science research process

A common view in sport science is that the research process reaches its end at acceptance of an article for publication. In parallel with this view, authors sometimes overlook the notion that the most important outcomes are dissemination and implementation of research results. The priority should be answering relevant questions that affect real people in a given clinical, sporting or community context [1]. Therefore, careful crafting of research questions and scientific rigour to conduct projects are merely a means of obtaining trustworthy and evidence-based outcomes to advance sports performance. However, the conceptually simple translation between quality research and the subsequent implementing of the practical applications is often disrupted along the way. This breakdown in the process is often a consequence of ineffective communication between sport scientists and the end beneficiaries of the research - the coaches and athletes. Assuming sport scientists conduct research that addresses relevant questions, maximising the gains of new knowledge for coaches and athletes centres on effective communication and a translation strategy. The challenge for sport scientists is to translate their research outcomes into practical strategies that benefit sport performance or exercise outcomes.

Sport science is the discipline that identifies, validates, develops and refines various protocols and strategies to improve sports performance. Contemporary sport science includes various disciplines such as sports nutrition, physiology, strength and conditioning, biomechanics, sports medicine, performance analysis and skill acquisition. Specialists focusing on each of these disciplines work with individual athletes and their coach, in a team sport setting, or in a general coordinator role for agencies and sporting organisations. With the involvement of so many different third parties, sport science can turn into a complex system of mul-

[1] Research Institute for Sport and Exercise, University of Canberra, Australia.
[2] Australian Institute of Sport, Canberra, Australia.

tiple simultaneous interventions that might interfere with one another rather than work synergistically towards the same goal [2]. Therefore, professionals usually work together to maximise training adaptations and help minimise the negative effects of training, such as an increased risk of fatigue, illness and/or injury. This team effort does not come without challenges, but integration of all these different disciplines is needed to enhance an athlete's or team's performance in minor or major competitions.

Sport science continues to evolve from evidence-based scientific research in related areas. It is arguable that science is generating knowledge at a faster pace than the coaching and sport science community can implement and benefit from. This is particularly true in the current digital age where gathering, creating and accessing vast information is an everyday practice, but best use of all the information challenges most individuals and organisations. As science and technology advance at a rapid pace, modern sport science is about translating knowledge from fields that might seem foreign to sport, but could be as useful as creating new knowledge. Contemporary research outcomes that might aid sports performance could derive from non-intuitive research related to new light materials used in racing cars (transferred to cycling technology), the military/NASA (for example, GPS tracking technology), and keeping athletes healthy (for example, haematological, microbiological and immunological monitoring). Wearable technology is among the latest advances in training monitoring, however, they also pose the challenge of adequately interpreting the data recorded as well as ensuring validity and reliability [3].

The benefit of translating this knowledge and research to sport could provide a competitive advantage if implemented correctly. Finding more effective ways of translating both sport and non-sport research outcomes is worth exploring for the sport scientist [4]. This process can be aided by coaching clinics and association/club meetings where more experienced coaches can share their experiences in implementing new ways and ideas derived from research. New coaches are more likely to take notice of what their mentor coaches advise as they have more affinity with them than sport scientists, especially if the new coach has had limited exposure to research. This approach would work well with experienced coaches who have the skill to interact with other professionals for their own development and his or her athletes. Clubs/national organisations can benefit from inviting external coaches as a professional development exercise for less experienced coaching staff.

The literature on best practice for how to apply sport science research is scarce. Aside a few examples looking into coach perceptions on the importance and the application of sports science [5] and how to best apply sport science to triathlon [6], the research body on the sports scientist's role is slim. A more authoritative and comprehensive overview of strategies for translating research in sport is needed. Other research areas, especially within the clinical and medical fields, have developed strategies to implement research outcomes for the benefit of patients [1, 7]. Some journals now feature a section where scientists summarise the practical applications of research manuscripts submitted for publication. This approach should encourage a growing body of easily applicable research in sport.

The modern trend of increasing numbers of support staff in sport has added a degree of complexity to the coach - athlete interaction. Coaches in contemporary sport often have to manage a large group of professionals all advising on different areas and sometimes with competing interests. As these support staff help maximise recovery as well as adaptations from training, while avoiding injury/illness, prioritising each area at any given time becomes crucial, hence communication and planning by the group is essential to realise the benefits of research. Sports have obtained a significant benefit from applying many of the latest evidence-based outcomes that sport science and related disciplines offer. However, unless there is harmonious interaction between these disciplines and research outcomes, this 'support' can prove distracting to the athlete's performance. Implementing research outcomes in a simple, carefully planned and effective manner is a challenge but also an opportunity.

Research outcomes worth implementing by definition are based on a very high likelihood of being clinically or practically significant. This generalisation somewhat contradicts the reality of a coach and an athlete, whose careers depend on the quality of performance on the day of a specific sporting event. Researchers need to generalise the observations obtained from a sample of the population (study participants) to the rest of the population of athletes with similar characteristics. For example, outcomes from a sample cohort that are male, over 18 years old and moderately active and healthy will be most relevant to the population of a similar description. Given that coaches and athletes are judged constantly on their performance, and their funding and scholarships schemes demand consistency within and between seasons, the sport scientist can struggle to implement a new idea that athletes and coaches are unsure how it might affect them directly. Of course, unless an athlete and/or coach tries something new, they will not know how they might benefit, despite an informed opinion based on the evidence from rigorous research. It is important to keep in mind that high performing athletes are a rarity in the general population given their genetic talent, extensive training and expert coaching. Most research is based on highly trained athletes, but few sports scientists manage to persuade elite athletes to participate in research. Consequently, the application and success of a new research idea needs to be ‘tested’ in training or minor competition by athletes to see its likely effect on major competition.

Sports medicine includes physicians and physiotherapists among other practitioners who have the responsibility of looking after the clinical side of athlete well-being. Although the majority of sports medicine research is based on improving and optimising clinical treatment of illness and/or injury, a significant effort is made in preventative strategies and for the athletes’ health and safety [8]. Similar to sport science, sports medicine seeks to apply the latest medical research knowledge to a sporting context, after understanding the reality of sport and the intricacies of physiological adaptations in well-trained individuals. So many of the issues of translating scientific research also apply to sports medicine research.

Facilitating the transfer of knowledge from scientist to coach/athlete is the responsibility of researchers and sport science practitioners who have the capacity to understand, conduct and critically analyse rigorous research data and apply it to a sporting context. However, both sport science and sports medicine face similar challenges in first identifying the underlying needs, integrating the practical applications of the latest research into the busy training and competition schedules of athletes, and disseminating research outputs to the wider sporting community. Moreover, the sport scientist has to develop the skill set to interact with peers from his or her own and other areas of research to continue their growth and development as a scientist. A growing opportunity to achieve this latter professional development is in academia-industry collaborations, where collaborative funding and expertise can benefit sport [9].

Adding to the already long list of skills required for the sport scientist is the obtaining of funds to develop research. Often sports scientists fulfil a role of a translator between researchers and coaches, athletes and sporting organisation, however, sport scientists can also develop new research of their own add high value to the team. Instead of having to revert to a third party, sport scientist and coach/athlete teams can identify and develop their own customised research projects that best suit their needs at any given time. Gaining funding grants to realise such research projects often falls on the scientist as sports run on an already tight budget. Academic allies that are eager to work with industry often seek matched funding opportunities where universities and sports contribute to the cost of running the research. Seeking collaborations with universities, government and private entities is another opportunity the sport scientist should develop. With limited funding opportunities directed to sport-related research, collaborations seem a smart approach, but researchers should disclose any conflict of interest when obtaining funding from commercial companies.

Application of research outcomes

As the demands of modern sport continue to evolve, scientists need to be adaptive and intuitive. The priority for the sport scientist should be answering relevant questions that affect real people in a given sporting, clinical or community context. Research outcomes from sport science studies are crucial for developing guidelines for high performance sport, exercise and physical activity. However, these applications can only be realised if the research process is shared, and results contextualised and translated for specific cohorts and other populations. For example, recovery strategies might differ between a contact sport and non-contact sports as would the nutritional interventions between a female gymnast and a male rower. Chronological and biological age of the athlete, training regime, competition demands, environmental challenges to overcome, and individuality among other factors will influence the acute responses and long-term adaptations to training. It is, therefore, the sport scientist that will fine tune concepts and research theory to find the best fit between evidence-based concepts and the individual athlete(s).

The main beneficiaries of sport science research are the coaches and athletes whom benefit from acquiring the evidence-based knowledge that has been translated and customised to their needs. Athletes and coaches do not have time, or often the specific understanding in complex areas or disciplines, to understand complex or highly technical research outcomes or their importance. In these situations, athletes and coaches will depend on a 'translator' to do so. Furthermore, implementation of strategies has to be practical, cost effective and time efficient, or otherwise the knowledge remains a theory and benefits go unrealised. To increase the 'utility' of research outcomes, dissemination, translation and practical applications that are viable need to be planned, developed, and evaluated. In the absence of any clear candidate who can take on this role in many cases, it is typically the responsibility of the researcher to manage this process in partnership with the other stakeholders: the sporting organisation, coach, athlete, support staff, related disciplines, and other members of the research team.

Development

Dissemination of research outcomes

Timely discussion and dissemination of research outcomes require effective strategies and appropriate technical and meaningful language for different audiences via traditional scientific publication, conference proceedings and social media strategies. Disseminating and communicating research knowledge should span scientific, medical and allied health disciplines, local, national and international contexts, and translation into non-scientific communities. However, the application of this knowledge has been variable and often inappropriately applied worldwide. The transferability of results obtained from highly trained athletes might not apply directly to the wider population, and vice versa. Therefore, researchers need to identify, develop and implement new ways of putting highly scientific information and outcomes into context using real world narratives, examples and case study approaches. This communication could be maximised by the use of online resources (social media, blogs/pages, emails and visual material such as posters and infographics) and jargon-free presentations or workshops to key industry and stakeholders. Of course, the language used in any of these formats should be appropriate to the type of communication used, and always in plain language. The research outcomes should reach the cohorts or population that would most benefit from it, and this responsibility lies partly with the scientist.

Case study – Translation of warm-up research in high performance swimming

It is generally acknowledged in the swimming community that warming up prior to competition is a worthwhile practice. However, warm ups have been poorly described in the scientific and coaching literature, and the extent to which different elements and formats are effective in enhancing performance is unclear. Furthermore, whether coaches actually implement evidence-based recommendations emanating from relevant research studies is unknown. We conducted a series of projects with the aim of enhancing warm ups and ultimately competitive performance in high level swimmers (see Figure 1). The challenge now is to how to translate each of the separate research study outcomes into a coherent message for the swimming community. Here we present a case study illustrating the challenges and opportunities for translation of sport science research using a research program examining the effects of warm-up to enhance swimming performance.

After identifying that maximising the warm-up for swimmers is vital, the first step in the research program was to undertake a comprehensive review of the physiology and practice of warm-up [10]. Although the requirement of detailed knowledge of the underlying literature is not paramount for the actual swimmer or sometimes even the coach, it is fundamental for the scientist. This review process was particularly important given the inconclusive nature of warm up (and swimming-specific warm-up studies) in the sport science literature and the timespan from previous reviews on the subject. The combination of a physiological (for scientists) and performance (for coaches) focus in the literature was deemed important during this review. While both swimmers and coaches are focussed on performance outcomes, sport scientists should understand the mechanisms behind the various strategies, practices and approaches (such as the pre-event warm-up) they promote.

The second step of the program involved a survey of coaches (both domestic and international) to characterise contemporary approaches and attitudes to warm-up practices in high performance swimming [11]. Engagement of end-users of the research (in this case the coaches) at the start of the program was deemed an important element in translation and implementation of the outcomes. Coaches identified four key objectives of the pre-competition warm-up: physiological (elevate body temperature and increase muscle activation), kinaesthetic (tactile preparation, increase "feel" of the water), tactical (race-pace rehearsal), and mental (improve focus, reduce anxiety). The pool warm up volume ranged from ~1300 to 2100 m, combining low-intensity swimming, drill work, with 3-4 race or near race-pace efforts (25-100 m; ~90-100% effort) finishing with 100-400 m easy swimming. Dryland-based warm-up exercises, involving stretch cords and skipping, were also commonly prescribed to prepare athletes for events between 50-200 m. Coaches preferred swimmers complete their warm-up 20-30 minutes before race start. Lengthy marshalling periods (15-20+ minutes) and the time required to don racing suits (>10 minutes) were identified as complicating issues. The combination of dryland-based activation exercises followed by pool-based warm-up routines seems to be the preferred approach taken by elite swimming coaches preparing their athletes for competition. While this anecdotal information is interesting in a descriptive sense, the primary outcome of this survey was to inform the design and methodology of subsequent experimental work, and importantly, the content and language of coaching resource material underpinning translation of the experimental outcomes.

Development of the experimental studies centred on a combination of pool-based and dry-land activities [12]. Initially, sixteen junior competitive swimmers completed a standardised pool warm-up followed by a 30 min transition and 100 m freestyle time-trial. Swimmers completed four different warm up interventions during transition: remaining seated wearing a conventional tracksuit top and pants, wearing an insulated top with integrated heating elements, performing a 5 min dryland-based exercise circuit, or a combination of passive and dryland. Swimming time-trial performance, core and skin temperature and perceptual variables were monitored. A dryland-based exercise circuit completed alone and in combination with a heated tracksuit jacket during transition can substantially improve sprint swimming performance. Attenuation in the decline of core temperature between the warm up and competition, and a reduction in start time, appear as likely mechanisms for this outcome. While few swimmers will have access to a heating jacket during transition, they can all perform simple exercises and wear a conventional tracksuit during the transition phase.

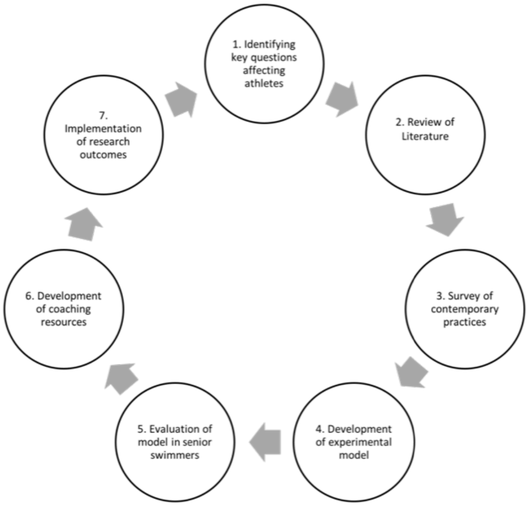
The initial development of the warm-up model was, as is often the case in swimming and many other studies, with junior or age-group swimmers/athletes. While benefits of the pool-based and dry-land exercises were established with the juniors, the critical question for the broader swimmer community was how these effects translate to senior swimmers [13]. Twenty-five senior swimmers completed a standardised pool warm-up followed by a 30-min transition phase and a 100 m freestyle time trial. During the transition phase, swimmers wore a tracksuit jacket with integrated heating elements and performed the dry land-based exercise routine (Combo), or a conventional tracksuit and remained seated (Control). A traditional pool warm- up coupled with passive heating via heated jackets, and dry-land exercises in the transition phase improved elite sprint swimming performance by ~0.8%. This magnitude of improvement is worthwhile and formed the basis of evidence-based recommendations to coaches and swimmers.

Transferability of effects is important in swimming, where there are several different event distances and strokes (freestyle, butterfly, backstroke, breaststroke, medley) [14]. Performance in the 100 m time trial was not substantially different in 10 breaststroke swimmers between the different forms of warm up. It appears that targeted passive heating, and completion of dryland-based activation exercises in the transition phase, does not enhance sprint breaststroke performance despite eliciting elevated skin temperature immediately before time trial commencement. So the translation message was that ‘one size does not necessarily fit all’ – other strategies are needed to enhance breaststroke swimming performance. We also encouraged coaches and athletes to become familiar with the heated jackets and activation exercises in training, or a minor competition, before using them for the first time at a major national or international competition.

A final research study investigated the timing of the warm up and magnitude of the benefits of combined warm up activities in the context of training and competition schedules [15]. There are thousands of sport science publications examining the effects of various exercise interventions and strategies, although not all are contextualised to the high level sporting environment. A substantial proportion of elite athletes train (and often compete) twice or three times per day prompting questions on the timing and likelihood of carry-over effects from one session to the next. The effect of a morning swim or priming session on subsequent swim performance has been a perennial question in the high performance swimming community. Thirteen competitive swimmers completed: a) a morning session of 1200 m of variable intensity swimming, b) a combination of varied intensity swimming with a resistance exercise routine or c) no morning exercise. Following a six hour break, swimmers completed a 100 m time-trial. We concluded that completion of a morning swimming session alone, or together with resistance exercise, can substantially enhance sprint swimming performance completed later the same day. Coaches need to consider how a morning priming or potentiation swim (competition or training session) might enhance subsequent performance later in the day or evening.

Transfer of research outcomes for the broader high performance swimming community involved briefing sessions for swimming scientists, coaches and athletes; distribution of scientific manuscripts to sport scientists and plain language summary sheets as well as a one page infographic summary for coaches [16]. Infographics involving visual display of data and content are proving to be a popular form of presenting research outcomes for athletes, coaches, and the general community.

Figure 1. A seven step model for the development, transfer and implementation of research examining the use of warm-ups in high performance swimming. Step 1 Identifying key questions. Steps 2 and 3 Comprehensive review of both relevant scientific studies and contemporary practices and approaches of leading swimming coaches. Step 4 A series of pool-based experimental studies using both junior and senior swimmers to develop an effective warm-up combining both pool swimming, dry-land exercises and wearing of a battery-powered heated jacket. Step 5 Extension of the warm-up protocol to senior swimmers across different events. Step 6 Preparation of easy-to-read plain language education materials and briefing sessions for swimmers and coaches, and provision of heated jackets and supervised dryland warm-up exercises on the pool deck prior to competition. Step 7 Implementation of research outcomes and subsequent evaluation to inform new or recurring key questions.



Case Study - Lessons learned

Although the program of swimming warm-up studies yielded several research publications and generated interest in the swimming community, some shortcomings were noted. A challenging issue facing researchers is the time needed to complete the research and report back to coaches, subjects and relevant stakeholders such as the national federation. Athletes and coaches understandably have a short-term focus, and seek rapid feedback and expect worthwhile recommendations be implemented immediately. In contrast, research studies typically take months to years from the time of conception, through the formal experimentation and data collection, to report preparation and final dissemination of outcomes. Distribution of preliminary outcomes, at least to the stakeholders involved (privately), can complement the lengthy process of research. There are now many ways to disseminate data online in a more time-effective manner, however, this might compromise the ability to publish in a journal afterwards, so care is needed.

The steps in the information or outcome dissemination process should be built into the study planning and design, and revisited regularly to ensure these milestones are achieved on time. Individual members of the research team could be assigned this task but as per industry standards, all researchers should approve and endorse the content of scientific publications, conference abstracts and digital media output.

Automated processing of reports will aid the preparation and distribution of individualised reports. These reports can be presented in two versions. The first version immediately after the data collection could feature raw data, descriptive data, previously established reference ranges, and figures and tables. This material can be prepared before the final data analysis and interpretation is completed. A second distribution to subjects with the final study outcomes would come at the end of the research project. This material would have been through the data analysis and interpretation process, but more importantly, with clearly identified conclusions, take home messages and practical applications. This information would need to be in plain language, or an infographic, for non-specialist readers such as coaches, athletes and officials. An executive summary should be provided as the first page of a fully detailed report, and prominent use of dot or bullet points to summarise the main outcomes would be welcomed by all.

Another identified issue in the research process was shortcomings associated with separate distribution of results to athletes, coaches and scientists. Experience shows that the better option is for sharing and interactive feedback involving the coach, athlete and scientist in a three-way discussion. Having all parties hear the same information at the same time is preferred. This approach avoids the problem of the sport scientist delivering different information advice to the swimmer that might run counter to the coach's requirements, position or opinion. The ideal situation is where all invested parties sit together at the same time to review the athlete's individual results, the group results/outcomes, and their likely significance. At this point corrective actions can be implemented to ensure the athlete continues to improve.

The life of the sport scientist in the 21st century is not an easy one [17]. The elite sports community can be difficult for sport scientists and their research outcomes to be heard above the media throng, social media and a competitive high profile environment. Nonetheless, the sport scientist can take confidence that high quality evidence-based research outcomes with practical application will be heard, provided the right message is presented at the right time in a format suitable for the target audience.

Recommendations

Here is a brief list to promote the translation and increase the impact of sport science research:

- Seek evidence-based knowledge that comes from sound and rigorous research studies; although application and translation to sports is key, robust research is a critical factor in developing effective coaching programs and training interventions.
- Where available, make use of communication, media and public relations experts in your organisation, or collaborating organisations, who have expertise to assist the translation and dissemination of research outcomes.
- Using posters in targeted areas to let people know about research activities and outcomes – instead of using them just to recruit participants.
- Think laterally about who the research beneficiaries, collaborators and other stakeholders might be. Start with a list of everyone who might be impacted by the research outcomes (e.g. elite athletes, recreational athletes, sports clubs, sporting organisations, etc.).

- Find professionals and expertise outside the primary scientific discipline that might contribute to the research from a different perspective and add value or valuable insights.
- Plan for internal as well as external workshop/presentations and invite the community to engage with the research team.
- Use social media to disseminate research updates and outcomes by using colourful charts of the most interesting findings to obtain the attention of the audience that might not have access or tendency to read detailed journal articles or attend conferences.
- Prepare an 'infographics' slide for your research. Infographics are an effective way to simplify and disseminate your research.

Conclusions

The communication skills of the modern sport scientist now expand beyond their specific field of expertise. The scientist needs to develop the skills, expertise and experience for effective translation of research outcomes. The final research outcomes need to be presented in plain language for non-expert users of scientific and/or technical information.

Collaborations, nationally and internationally, matching research funds, and applied research outcomes are fast becoming priorities for many successful sport science projects. Funding agencies now expect real world applications and a substantial practical return on the investment by stakeholders, participants and researchers.

Although researchers are mostly judged on publications and research income, research teams should commit to the social, community, and ethical responsibilities in their chosen field of study, and the impact of their research in guiding clinical and sport training practices.

References

1. Assael, L.A., Translating science: from idea, to research, to clinical practice. J Oral Maxillofac Surg, 2005. 63(6): p. 729-31.
2. Balague, N., et al., Sport science integration: An evolutionary synthesis. Eur J Sport Sci, 2017. 17(1): p. 51-62.
3. Cardinale, M. and M.C. Varley, Wearable Training-Monitoring Technology: Applications, Challenges, and Opportunities. Int J Sports Physiol Perform, 2017. 12(Suppl 2): p. S255-S262.
4. Eisenmann, J., Translational Gap between Laboratory and Playing Field: New Era to Solve Old Problems in Sports Science. Translational Journal of the American College of Sports Medicine, 2017. 2(8): p. 37-43.
5. Martindale, R. and C. Nash, Sport science relevance and application: perceptions of UK coaches. J Sports Sci, 2013. 31(8): p. 807-19.
6. Millet, G.P., D.J. Bentley, and V.E. Vleck, The relationships between science

and sport: application in triathlon. Int J Sports Physiol Perform, 2007. 2(3): p. 315-22.

7. Scott, I., The evolving science of translating research evidence into clinical practice. Evid Based Med, 2007. 12(1): p. 4-7.
8. Pyne, D.B., et al., Probiotics supplementation for athletes - clinical and physiological effects. Eur J Sport Sci, 2015. 15(1): p. 63-72.
9. Asadullah, K., et al., Industry-academia collaborations for biomarkers. Nat Rev Drug Discov, 2015. 14(12): p. 805-6.
10. McGowan, C.J., et al., Warm-Up Strategies for Sport and Exercise: Mechanisms and Applications. Sports Med, 2015. 45(11): p. 1523-1546.
11. McGowan, C.J., et al., Current Warm-Up Practices and Contemporary Issues Faced by Elite Swimming Coaches. J Strength Cond Res, 2016. 30(12): p. 3471-3480.
12. McGowan, C.J., et al., Heated jackets and dryland-based activation exercises used as additional warm-ups during transition enhance sprint swimming performance. J Sci Med Sport, 2016. 19(4): p. 354-358.
13. McGowan, C.J., et al., Elite sprint swimming performance is enhanced by completion of additional warm-up activities. J Sports Sci, 2016.
14. McGowan, C.J., et al., Evaluating Warm-Up Strategies for Elite Sprint Breaststroke Swimming Performance. Int J Sports Physiol Perform, 2016. 11: p. 975-978.
15. McGowan, C.J., et al., Morning Exercise Enhances Afternoon Sprint Swimming Performance. Int J Sports Physiol Perform, 2016. 6: p. 1-23.
16. Le Meur, Y., Infographics, in https://ylmsportscience.com/2015/09/25/basics-warm-up-strategies-for-sport-performance-by-ylmsportscience/, Y.L. Meur, Editor. 2015.
17. Burke, L.M., Communicating sports science in the age of the twittersphere. Int J Sports Nutr Exer Metab, 2017. 27(1): p. 1-5.

Periodization in sport training: traditional, blocks and polarized

Jose Maria González Ravé[1]

Background

Variation in training is known as one of the key factors for achieving success in the training schedule to optimise sports performance (Fleck, 1999). Training loads and their proper organisation constitute one of the trainer's most important tasks for helping athletes properly adapt their bodies, thereby optimising their maximum sports performance. Although an exhaustive analysis of the training loads has already been conducted in Chapter 3, our proposed investigation emphasises the interconnection and distribution of these loads. The distribution of loads alludes to their dynamics and organisation in the various cycles of training and is the way the various loads are placed in a session, microcycle, mesocycle or macrocycle (Verkhoshansky, 1990; Siff & Verkhoshansky, 2000; Navarro, 2000). The concept of load interconnection indicates the relationship among the loads of different orientation when combined over time (Siff & Verkhoshansky, 2000:430). These concepts represent an interesting approach for research in our field, given that the transition of one training load to another should represent the transition to performance levels other than the current level. Research in this field therefore represents progress in the control of these training directions.

The conceptual development of this chapter will highlight the process of training and the variants in its periodization as a noteworthy element within the distribution and interconnection of training loads and will show the potential gaps in research that serve as a basis for presenting potential future research lines.

Training Periodization

Periodization is one of the most important concepts in training. The term has its origin in the period, which is a portion or division of time within which we find smaller and easier to manage divisions called training periods (Bompa, 1999).

The concept of periodization originated in Eastern Europe and was adapted to the planning of modern training in the 1960s by sports scientists such as Matveyev in the Soviet setting and Bompa in the Czechoslovakian setting (Norris & Smith, 2002; Wathen, 1994). Subsequently,

[1] Faculty of Sport Sciences. University of Castilla la Mancha (Spain)

American scientists such as Stone and O'Briant modified Matveyev's study, adding phases to the preparatory period (Norris & Smith, 2002; Wathen, 1994; Wathen & Role, 1994).

Periodization is the cyclic and gradual ordering of training exercises, following principles of specificity, volume and intensity to achieve high levels of sports performance in the most important competitions (Wathen & Role, 1994; Fleck, 1999). Plisk and Stone (2003) defined periodization as a planned distribution or a variation in training methods by means of time cycles. In this respect, it seems that periodization is a fundamental concept for achieving sports performance. Hoffman (2002) considered 2 types of periodization to achieve performance: linear models, considered as the classical form of periodization design, and nonlinear models (undulatory), in which the training volume and intensity varies from session to session, as shown in Table 1.

	Series	Repetitions	Rest between series
Day 1	3-4	8-10 RM	2 min
Day 2	4-5	3-5 RM	3-4 min
Day 3	3-4	12-15 RM	1 min

Table 1. Example of Nonlinear Period Training

The rational, deliberate and studied organisation of the training content is a key factor for good periodization. The distribution of training content within the various training structures is a seldom studied aspect of planning, which trainers conduct by recommendations or by practical experience gained from day-to-day practice.

The objective in the periodized models is to attempt to maximise the principle of overloading and ensure the correct relationship between stimulation and recovery. The principle of overload in sports training is the process by which the neuromuscular or cardiorespiratory system is stimulated by larger loads, causing an adaptation. The periodized programs attempt to maximise this adaptation by changing the magnitude of the loads and thereby increasing the neuromuscular and cardiorespiratory system's response capabilities (Howley & Franks, 1986; Stone, O'Bryant & Garhammer, 1981).

Periodized versus Nonperiodized Models

Periodized strength training programs appear to produce greater gains than nonperiodized programs of one or multiple series (Fleck, 1999, Stone, O'Bryant & Garhammer, 1981, Rhea et al., 2003). The first of the classical studies in this field dates from the start of the 1980s. The study compared a periodized programme with other nonperiodized programmes for 6 weeks, performing 3 weekly sessions, improving 1 RM in squats and power in the vertical leap (Stone, O'Bryant & Garhammer, 1981). Other studies have compared undulatory and linear periodized programs and have showed that the inverse linear programmes in which the volume is increased, and the intensity is reduced are more effective than the undulatory or linear incremental programmes (Rhea et al., 2003). In the study by Willoughby (1993), there were no significant differences during the first 8 weeks in the total volume of work between the periodized model and the 2 training programmes of multiple series. After 8 weeks, the volume of training was decreased compared with the other programmes. From there to week 16, there were significant differences in 1RM in bench press and squats between the periodized model and the other models, even though performance was also improved in these models. Baker et al. (1994) found no significant differences in maximum strength in squats, bench press or vertical leap between the undulatory and linear periodized models, during 12 weeks in which the total volume and intensity (%) were similar in both programs, which allowed for the variations between one and the other to be attributed to the difference between the programmes. Despite finding no significant differences in maximum strength between the periodized and nonperiodized models, other studies found improvements exclusively in the group that exercises according to the periodized model (Plisk & Stone, 2003).

González-Ravé et al. (2007) compared the efficacy of periodized programs against that of nonperiodized programs during 5 weeks of training in physically active participants (Sports Science students) with the intention of improving maximum power in performing the bench press exercise. Twenty-two individuals participated in the research study and were divided into 2 groups: a nonperiodized group (9 participants) and a periodized group (13 participants). The nonperiodized group performed 5 series of 6 repetitions 2 times a week for 5 weeks, reassessing maximum power at 2.5 weeks. The periodized group performed 5 series of 6 repetitions the first week, 4 series of 5 the second week, 5 series of 7 the third week, 5 series of 8 the fourth week and 4 series of 6 the fifth week, reassessing the power halfway through the study. The total volume and intensity were evenly matched. The results of the study showed that the power increased significantly in the intermediate measurement (13.26%, $p<0.05$) compared with the pretest measurement in the periodized model, while in the nonperiodized model, the significant percentage increase was 19.83%. However, in the final measurement compared with the intermediate measurement, the power in the periodized model only increased 2.86% (although not significantly), while in the nonperiodized model, the power decreased significantly (10.21%, $p<0.05$) compared with the intermediate measurement. We therefore conclude that there are no significant differences in the gains in maximum power between the 2 groups. The results in the untrained participants also showed limitations in the applicability of these models to highly trained athletes.

A more recent study by Kell (2011) determined the influence of 12 weeks of periodized training on changes in strength in young male and female sports enthusiasts with prior experience in nonperiodized strength training. The results showed that 12 weeks of strength training following traditional periodization induced significant strength gains in women (>30%) and men (>25%) with approximately 11 months of prior experience in nonperiodized strength training.

One of the most important contributions in the research on the effectiveness of training periodization was by Rhea and Alderman (2004), who performed a meta-analysis of the results of periodized versus nonperiodized programmes based on the publication of scientific studies from 1962 to 2000 for the selection of studies to be included in the statistical analysis. The keywords for the search were periodization, strength training, anaerobic exercise, resistance training and weightlifting.

Rhea and Alderman (2004) concluded that periodized training is more effective than nonperiodized training for men and women and for individuals of varying levels of preparation and ages and that when one considers the variables of volume intensity and frequency in the training program; this is manifested in adaptations of better physical performance.

The Classical Theory of Periodization

The theory of periodization was originally defined by LP Matveyev in 1965 as an update to the study published in 1962. The annual training cycle is conventionally divided into 3 main phases: the preparatory phase, the competitive phase and the transition phase (Bompa, 1994). Wathen (1994) indicated that each mesocycle has a different duration, lasting from weeks to months, depending on the type of sport, the athletes' sports performance, competitions, intended objectives and time between competitions. Each mesocycle contains several microcycles, which are generally 1-week periods, although they can be fewer training days. The microcycles are defined as a series of training sessions, organised rationally in a short period of time (García, Navarro & Ruiz, 1996). They are not finished processes but rather represent organisational structures that will complete the processes with the mesocycles.

During the 1950s and with the success of the Soviet delegation in the Helsinki Olympic Games, the scientist Lev Matveyev presented and popularised his general theory of sports training based on biological laws and in particular the general syndrome of stress adaptation. The definition of sports fitness disseminated by Matveyev (1977) is defined as the condition of optimal predisposition for achieving sports goals, which is possible to achieve through a detailed organisation of the training program in periodic cycles. Matveyev defined these cycles as the preparatory period, the competitive period and transitory period (Fig. 1). He also established that sports conditioning goes through 3 states: acquisition, maintenance and temporary loss of this sports fitness (Matveyev, 1977; Navarro, 2000).

The fundamental pathway for the acquisition and maintenance of sports fitness is based on managing and modulating the volume and intensity of the stimuli, tasks and exercises, which, along with the complexity of the exercise, constitute the training load. The programmes include modulation of the volume and intensity in an inversely proportional manner. The preparatory period is started with increasingly greater volumes and moderate intensity. Subsequently, during the maintenance period, this situation is inverted to reduce the volume of training and increase the intensity to prepare the body for competition. A supreme state of performance is thereby achieved, which is manifested in the previously mentioned sports fitness (Matveyev, 1977; Baker, et al. 1994; Bompa, 1994, 2000)

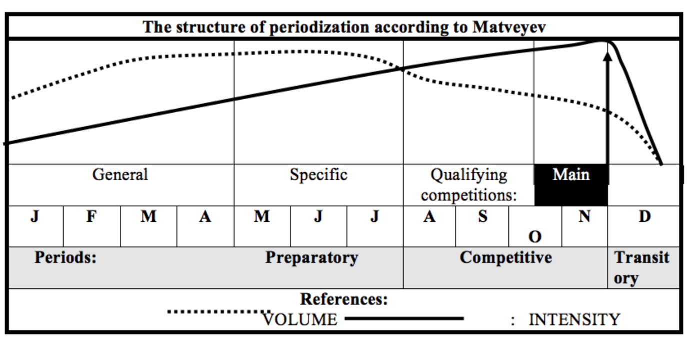


Figure 1. Example of the Classical Model exposed by Matveyev.

Foundations of periodization

The original basis of periodization was the general adaptation syndrome proposed by Hans Selye (1956), who described the body's generic response to stress (Wathen, Baechle & Earle, 2000). According to this model, the initial response phase to any stress is characterised by shock or alarm (Selye, 1956; Wathen, Baechle & Earle, 2000). After this, there is a supercompensation phase in which the body adapts to increase the specific capabilities affected by the stress (Selye, 1956; Wathen, Baechle & Earle, 2000).

The homeostasis process is caused by the training load the body is subjected to, which produces a stimulation that leads to an imbalance (or heterostasis) in the anabolic and catabolic processes, which the body once again tries to rebalance. This righting is manifested in an increase in anabolic processes to protect the structure from excessive exhaustion (Fry et al., 1991). This means that the regenerative processes attempt not only to recover the athlete's initial level but also to exceed it. This phenomenon is understood to be a protective mechanism to prevent a future emptying of reserves in the event of greater repeated loads. This phenomenon is known as supercompensation (Grosser, Brüggemann & Zintl, 1989; Fry et al., 1991). In principle, supercompensation can only be related experimentally to the processes of glycogen metabolism. Transferring the supercompensation model to other metabolism settings does not appear possible (Martin Carl & Lehnertz, 2001). Figure 2 shows a graphical representation of these processes. In the most current literature, the term supercompensation may be replaced by that of adaptive reconstruction, given that adaptation to training loads is not produced equally in all the body's systems (Siff & Verkhoshansky, 2000).

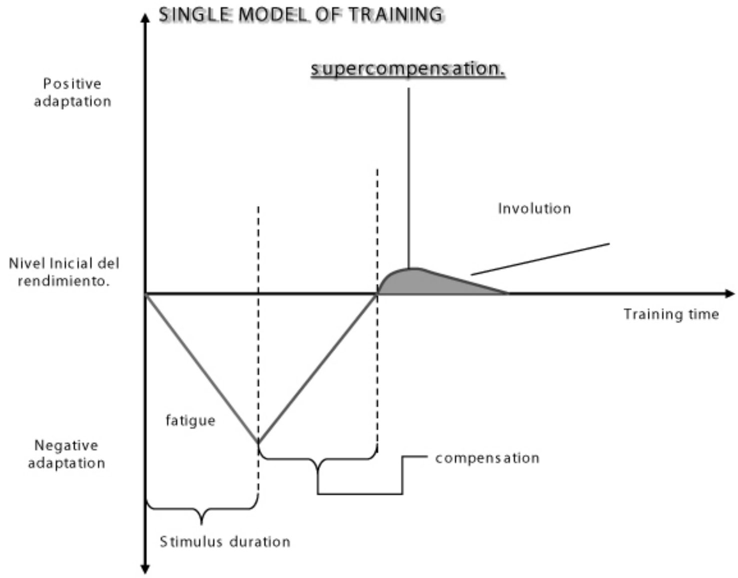


Figure 2. Explanatory diagram of the adaptation processes in the body. *(Yacovlev, 1977, cited by Grosser, Brüggemann and Zintl, 1989).*

This process of adaptation subsequently defines a theoretical model of sports training known as the **Unifactorial Training Model** (Siff & Verkhoshansky, 2000). Based on the principle of supercompensation, this model establishes how the body hypothetically adapts to a higher performance level in response to a repeated training load. Matveyev (1980: 48) presents this process as the overload and rest.

The systems theory has had considerable influence on sports training. A system is an entity characterised by at least one input and one output related to the input through a mathematical function (Busso & Thomas, 2006). The output corresponds to the system's response to a stimulus represented by the input. The function shows the system's behaviour using the determinants of sports performance in a specific sport. Figure 3A reflects the schematic representation of the system in a general manner, according to the characteristics established by Busso & Thomas (2006). Figure 3B illustrates the systemic application to sports training in such a manner that the input is represented by the dose of training performed, the system is represented by the athletes and the output is reflected by the subject's performance. This model is highly simplistic in its formulation because the accumulation of training loads produces a variation in the type of fatigue it causes and, in the body's, subsequent adaptation to a performance level that is expected to be higher. Moreover, the model omits other factors outside the training itself that affect performance such as psychological, biological and tactical preparation.

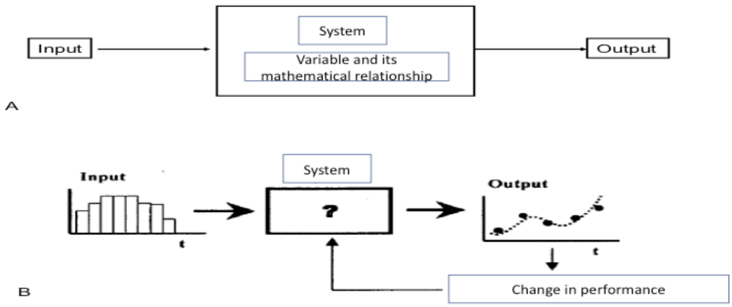


Figure 3. Schematic representation of the systemic model applied to sports training.

It has been assumed that the preparation of athletes is not an analytical and unilateral process but rather a complex system, composed of several subsystems related to the athlete's various spheres involved in improving their sports achievements. For Matveyev (2001), the preparation is determined by the training system, the competition system and the use of "complementary" factors of various types, such as general life regimens and specialised diets. Without the competition of these factors, the sports preparation system would be deficient.

Thus, the sports training system considers the individual as a whole, given that the individual only performs their vital functions in this manner, thereby opposing the reductionist concept of understanding the individual from just their biological side.

Relationship between Sports Fitness and Training Periods

Sports fitness is defined by Matveyev (1993) as the state of optimal predisposition (the best) for achieving sports goals, which is acquired by athletes due to the corresponding preparation in each new step of the sports improvement. Sports fitness should cover all aspects in their entirety, both physiological and psychological.

Thus, the process of developing sports fitness comprises 3 phases (Matveyev, 1983):

- Stabilisation
- Maintenance
- Temporary loss of form

Figure 4 shows a representation of these phases and their characteristics.

	Development phases of sports fitness	Training periods	Main objectives
1	Acquisition	Preparatory	Formation of pre-requisites for sports fitness. Accumulation of motor and multilateral coordination capabilities. General motor development.
2	Stabilisation	Competitive	Gradual improvement of the state of preparedness. Achievement of stable preparation, raising the results with a certain degree of variation
3	Temporary loss	Transition	To interrupt the training with heavy load To facilitate active recovery Renewing the athlete's adaptation reserves

Figure 4. Phases of the development process for sports fitness and their correspondence

The distribution of training loads during the training process.

For Verkhoshansky (1988), there are 2 types of variants for generating the adaptation in athletes. The first (A) consists of applying loads of notable volume, which cause considerable mobilisation of energy sources and that produce prolonged and deep changes in homeostasis. This type of training is temporarily organised into 3 to 4-week mesocycles, after which a rehabilitation break of 7 to 10 days is needed. These mesocycles are used for 18 to 22 weeks. This type of strategy is mainly used by high-level athletes and for rapid strength. This variant is related to concentrated loads (Issurin & Shkijar, 2002; Issurin & Lustig, 2004) and began to gain strength in the 1980s as a criticism and alternative review of the gradual load model around Matveyev periodization (Issurin & Shkijar, 2002). The concentrated loads models are closely related to the particularity of their effects, known as residual training effects (Issurin & Lustig, 2004).

The second variant (B) consists of the gradual increase in functional indices and is expressed in the case of a moderate and continuous volume of training loads. In this variant, periodic and short-term changes are caused. Thus, the body's homeostasis and energy reserves are compensated during the training cycle. This type of training is temporarily organised into longer cycles compared with the concentrated load systems (specifically 5 to 6 weeks), after which a rehabilitation break of the same length as the first variant is needed. This form of adaptation corresponds to the traditional training periodization idea of Harre (1987), Matveyev (1977) and Stone, O'Bryant & Garhammer (1981).

Each variant presents completely different adaptation rhythms in terms of the elapsed time to reach the sports performance and are represented graphically in Figure 5.

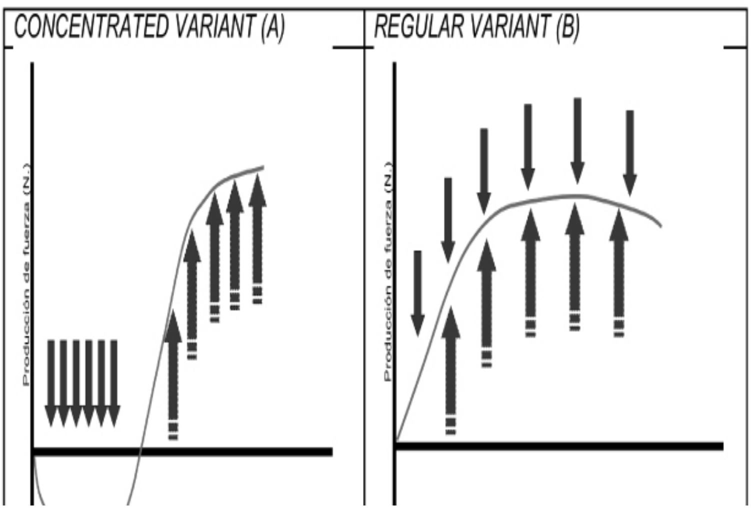


Figure 5. General diagram for the various types of body adaptation reactions to loads according to their distribution.

The Classical Periodization Models: General Preparation vs. Special Preparation. Workload Dynamics.

The workload can be divided uniformly in the cycle (regular or distributed workloads), which produces a uniform distribution of the means during the annual training cycle, or concentrated in defined phases of the annual cycle (concentrated loads). This distribution of regular loads (seen in topic 2) are those that configure the periodization structure of the classical model.

Matveyev (1980) based his periodization model on a general work paradigm of high volume/low intensity during the first part of the development of sports fitness, known as the preparatory period. The model then proceeds to a specific work order of the specialty in a low-volume/high-intensity regimen, which is described as the competitive period. The main components to consider in any sports training program are volume, intensity and frequency or number of training sessions, which were analysed in topic 3. Most experts in training theory and methodology agree that these components determine the load magnitude and therefore the response and adaptation to training (Matveyev, 1977; Navarro, 1999, 2010). The training content corresponding to the basic, specific and competitive levels of the sports discipline is conducted in a distributed and regular manner over the course of the various periods and phases of the cycle. Meanwhile, the total workload increases gradually over the course of the cycle, with a greater emphasis on volume during the general phase of the preparatory period and on intensity during the specific phase of the preparatory period and during the competitive period.

The Structure of the Classical Matveyev Model

Matveyev (1977) structured his macrocycle into 3 long periods during the season (Fig. 6):

1) Preparatory Period
2) Competitive Period
3) Transition Period

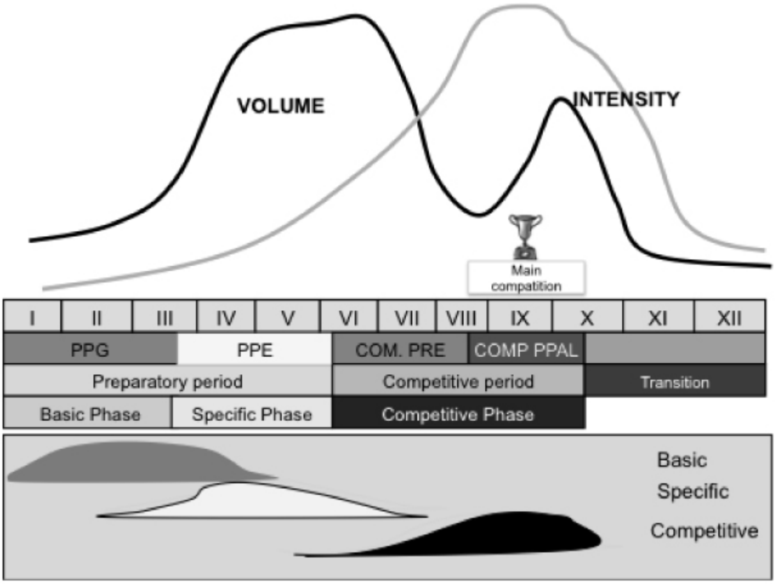


Figure 6. Classical Matveyev model (1977). PPG: General; PPE: Specific

During the preparatory period, the premises and conditions necessary for the acquisition of sports fitness are created.

The competitive period ensures the maintenance of sports fitness and is applied to achieve sports success.

The transition period arises from the need to protect athletes from potential injuries, providing active rest to protect from overtraining.

Each period's duration depends on the sports specialty and on the athletes' condition. In principle, the preparatory period cannot be shorter than required in the specific circumstances for acquiring sports fitness. The competitive period cannot be longer than that permitted by the possibilities of sports fitness maintenance without putting the subsequent process in jeopardy. Typically, these processes are determined by the standard year (Matveyev, 1993). The time recommendations provided by Matveyev (1993) are as follows:

- Preparatory period: 3-(4/5) months.
- Competitive period: 1-(2/5) months.

The preparatory period is subdivided into phases of general and special preparation. The main purpose of general preparation is to establish the functional basis for training, thereby improving the physical condition (Navarro, 2000). For Matveyev (2001), the term general preparation means something that cannot be reduced to sports specialisation, but rather creates and optimises the context of the athlete's progress in the chosen sports modality by means of the contribution to the general increase in the level of the athletes' functional possibilities, their multifaceted development and their enrichment with the knowledge, skills and habits, which in one way or another contribute to sports improvement. When applied to sports with technical components, we should (in addition to raising the body's functional capabilities) apply a range of motor foundations and skills to the technique. In the strategy-tactics of team sports, we need to support all the systems involved as well as the basic theoretical aspects of the game (Hernandez Moreno, 1988).

Matveyev (2001) stated that special preparation starts with general preparation, which progressively moves towards the objective of specialisation that, with growing depth, adapts the athlete to the chosen competitive activity. In the special preparation, the objectives for physical preparation are directed towards the development of specific physical qualities. The bases for the motor capabilities and techniques need to be created according to the specific requirements of each sport. In terms of the technique and tactics in team sports, we start to introduce these activities in their actual context. The theoretical aspects follow the same direction (Hernandez Moreno, 1988).

The competitive period needs to be subdivided into 3 parts:

An early competition phase in which we seek to develop the specific motor and technical capabilities, an increase in the athletes' potential so that they can take part in a series of competitions but without achieving the maximum level in the competitions but rather as preparation for the next period, which contain the main competitions.

The main competition phase is the most important part of the season. Training during this period is characterised by maximum, specific intensity similar to that of the competition. The main part of the exercises consists of modelled training. There may be competitions prior to the important ones.

The final competition phase is not a macrocycle component but can appear because the schedule of competitions can continue after the main competition. This involves maintaining the form insofar as still competing but considering fatigue in the main phase.

The transition period is a rest interval for establishing the means for proper recovery, to start the next season.

Traditional periodization can be established based on 1, 2 or 3 peaks of form (Fig. 7), considering particular competitive periods in which we wish to establish appropriate tuning. However, the premises on which this design are based allow for only one peak in form to be established (Bompa, 1999; Bompa & Haff, 2007).

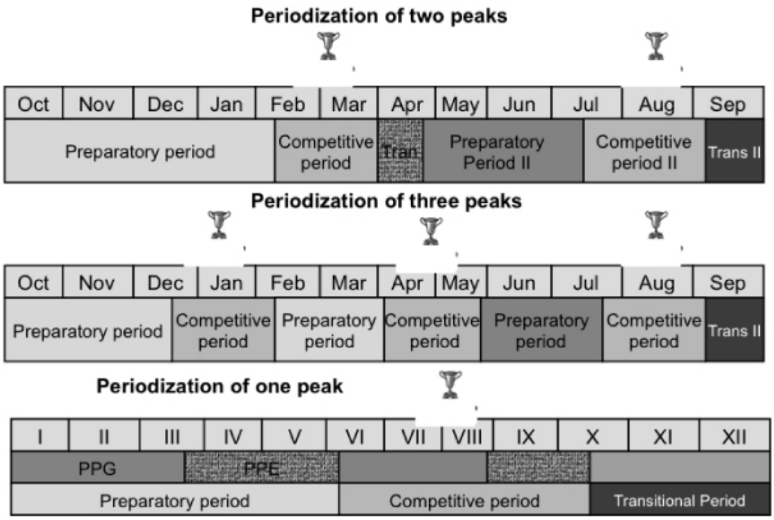


Figure 7. 1-peak, 2-peak or 3-peak Periodization.

However, the regular loads model still appears to be in use, as shown by the studies of Gorostiaga et al. (2006) and Granados et al. (2008). These scientific studies support the benefits of the classical periodization model given that both handball (Gorostiaga, 2006, Granados, 2008) and volleyball (González Ravé, Arija & Clemente, 2011) show significant improvements in physical condition during a season after the use of this organisation and the interconnection of training loads.

Criticism of the Classical Theory

In recent years, sports training has undergone several changes compared with classical periodization, which used to be employed for several reasons. One of the most important of these reasons has been a series of elements that were used to develop a theory of training by classical authors such as Matveyev and Zatziorski. According to Selujanov (1999), these do not consider the studies by Vorobiev on weightlifting or by Bondarchuck on launchings, which contain descriptions of training structures based on theoretical principles aimed towards adaptation. In Selujanov's opinion (1999), this was the big mistake by Metveyev. Moreover, Matveyev training periodization has been criticised by authors of other training methodologies from the Soviet school and Eastern countries, such as Verkhoshansky, who criticised the periodization of training. According to Verkhoshansky, the technique used to structure sports training is very rudimentary, *"… knowing the typical microcycles, which are formed like children's construction blocks, the following larger part (mesocycles) that in turn configure the large microcycles…"* (Platonov, 2000:88). However, the author later softens this criticism declaring that the process, although seemly analytical and separated among the existing elements, and the final result tells us how much more significant are the hidden connections of these elements that materialise in the continuity and the interrelationships of the effects obtained. According to Platonov (2000), these criticisms by Verkhoshansky are not a response to an updated reflection of the knowledge of current periodization, but rather a criticism of the postulates performed in the 1950s and that have been updated by Matveyev (2001).

In one of their more recent publications, Issurin (2008; 2010), mentioned the need to change the old theory of training and accept a new implementation of the modern demands for competitive swimmers.

The same author highlighted 4 weak points in traditional periodization:

- Considerable reduction in training volumes.
- The conflict resulting from the mixture of multiple skills trained simultaneously (mixed training programs).
- Insufficient training stimulus to help highly qualified athletes to continue with the progress (results of mixed or concurrent training).
- The inability to maintain frequent peaks of form during the season.

These same limitations of classical periodization had already been identified by Verkhoshansky (1996; 1999). Continuing with the proposal by Issurin of including of the blocks method (Block Periodization, also known as ATR) in the preparation programs for elite swimmers, Issurin (2010) established that this method presented 3 clear advantages compared with the traditional periodization method:

- Frequent performance peaks within the same competition year.
- Deep and specialised focus on the effects of training in a relatively short time;
- The recognition that the swimmers have a continuous state of general physical fitness in which a specialised block overlaps the effects of specialised training.

The New Periodization Models (Blocks or ATR Model)

The structure of concentrated loads is subsequent to that of regular or distributed charges. This structure is in response to the new demands of the current structures of high-level sports. We begin to question the antiquated and immovable theories of training based on the presumptions of classical periodization of Matveyev (1965) and Harre (1957 and 1969) (Selujanov, 1999; Tschiene, 2001; Issurin & Shkijar, 2002). The concentration of loads allows us to use highly concentrated training instead of a complex development of numerous capabilities. This training allows for more selective, immediate and cumulative effects than through the conventional model.

For Navarro (2000), the idea of the contemporary concept is based on the following:

1) The concentration of training loads on specific capabilities or specific training objectives (capabilities/objectives).
2) The consecutive development of certain capabilities/objectives in specialised training blocks or mesocycles.

Figures 8 and 9 show an example of periodization based on a structure training model called ***blocks. This model is based on the use of concentrated training loads.*** The concentrated loads are based on the principle of residual effect that the stimulus leaves on the athletes' body. The organisation of these loads seeks to delay those that have a greater residual effect. The lower the residual effect these loads have, the closer they are to the competition, as shown by the example of Issurin & Shkijar (2002) in Figure 9. The concept of residual effect, although intuited in some manner in the classical model, does not appear in sports training literature as such until mentioned by Counsilman & Counsilman (1991).

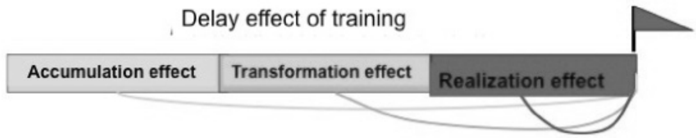


Figure 8. Residual effect of concentrated training loads following a blocks model.

As can be observed in Figure 9, those capabilities that have a longer lasting residual effect are placed further from the competition. Moreover, this organisation places generic basic capabilities such as aerobic resistance and strength in the first phase. More specific capabilities such as anaerobic resistance and strength resistance, which have a smaller residual effect than those in the previous phase, are placed in the second phase. Finally, those capabilities more closely related to the competition situation, which have a smaller residual effect, are situated in the phase closest to the competition. To promote the residual effect of the basic and specific capabilities, memory miniblocks of 2-3 days are employed to prevent a reduction in the previously trained capacity. Each selective load has a specific temporary effect (residual) on the body. The charges are heterogeneous depending on the type of metabolism requested. Issurin & Shkijar (2002) determined the duration of the residual effects of load training in the following time references:

- Alactic anaerobic capacity: 5 days.
- Muscular endurance: 14 days
- Anaerobic endurance: 18 days
- Maximum strength: 30 days
- Aerobic endurance: 30 days

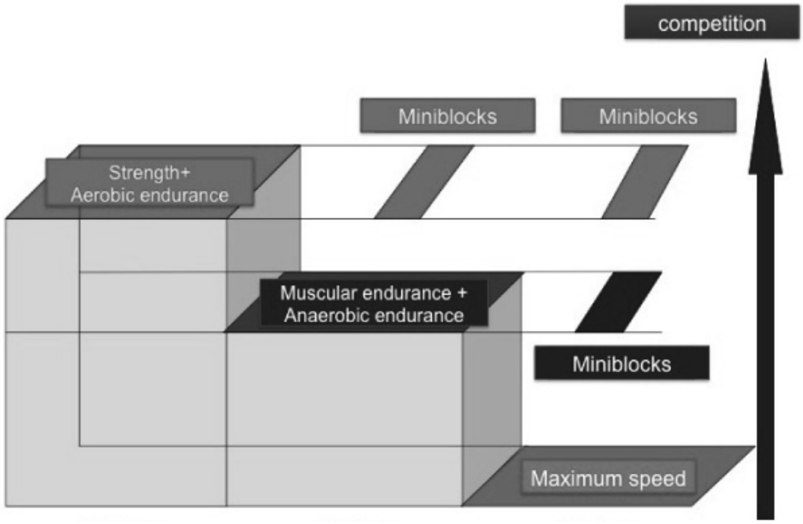


Figure 9. Prolonging the effects of training using training load miniblocks (Issurin & Lustig, 2004).

The factors derived from the residual effect of concentrated loads provide the following ***practical consequences on high-level sports training*** (Issurin & Lustig, 2004):

- The duration of the mesocycles varies from 2 to 6 weeks, although for Verkhoshansky (1988) the ideal period would be 3 to 4 weeks. This variability among authors could be due to a lack of scientific foundation for many of these approaches (Gorostiaga, 2000). For Issurin & Lustig (2004) and Gorostiaga (2000), a 4-week mesocycle is more advantageous than a longer cycle because the residual training effects are better taken advantage of and the athletes' biological response is more appropriate.
- In the competitive period, the competition mesocycles are shorter than in the preparatory period, because stress, the product of competition, decreases the residual effect of training in successive mesocycles. Moreover, physiological and emotional stress increases the catabolic processes, causing a reduction in muscle mass and reducing the residual effect of training in the maximum and explosive strength. Just as a highly intense activity with a marked anaerobic metabolism, the stress causes a loss in

aerobic capacity accompanied by a reduction in the anaerobic threshold.

- The use of 2 to 3-day memory miniblocks prevents a reduction in initially trained capacity and with it the short-term residual effect.
- Athletes with more years of training can perform longer transition periods and lower training volumes (15-30% less) than younger athletes.
- Thus, the training cycle of veteran athletes is shorter due to a longer transition period. The longer duration of the residual effect of training offers the possibility of performing a lower load volume.

Structure of the ATR (block) model

In the concentrated training model, the number of trainable capabilities in a mesocycle should be decreased to 2 motor capabilities and 1 capability that is characteristic of the technique. The capabilities to be worked on should be established so that a simultaneous task is set up between each mesocycle, considering the effects produced by the task through the interaction of loads (see the mesocycles section).

There are 3 mesocycles within the macrocycle:

- The accumulation mesocycle attempts to raise the athlete's technical and physical potential.
- The transformation mesocycle attempts to transform the potential of the physical and technical capabilities by specific preparation.
- The implementation mesocycle attempts to achieve maximum results within the workout performed.

This ordering of mesocycles, and as a consequence of its microcycles, is based on the cumulative residual effect produced by the earlier workout. In other words, the accumulation work should be maintained longer than the transformation workout, which should be maintained longer than the implementation workout in relation to its training content and the duration of the effects it causes. Thus, each mesocycle is based on a workout that develops the following capabilities based on the premise by Issurin & Lustig (2004):

MESOCYCLE ACCUMULATION:

- Aerobic training.
- Maximum strength.
- Greater residual effect.

MESOCYCLE TRANSFORMATION

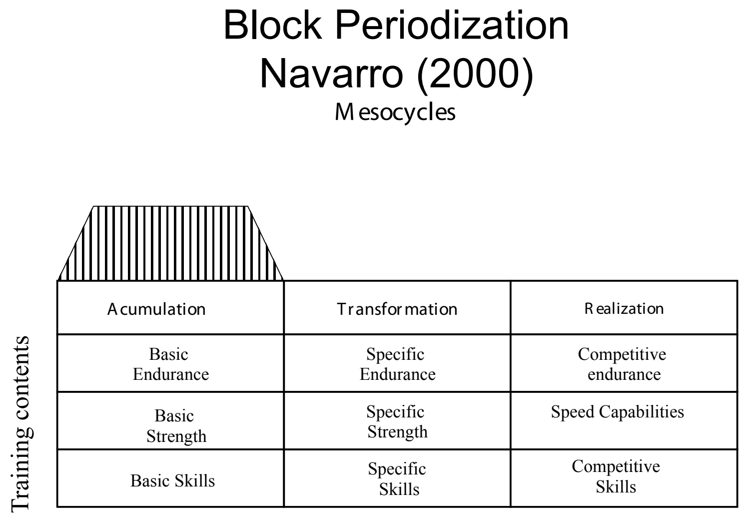
- Strength resistance.
- Anaerobic glycolytic capacity.
- Medium residual effect.

MESOCYCLE REALIZATION

- Alactic anaerobic training.
- Training in competitive conditions
- Specific tactics.

Smaller residual effect.

This distribution can be observed in Figure 10.



Thus, the mesocycles run during the season in several macrocycles, which constitute the ATR model, as can be seen in Figure 11 below:

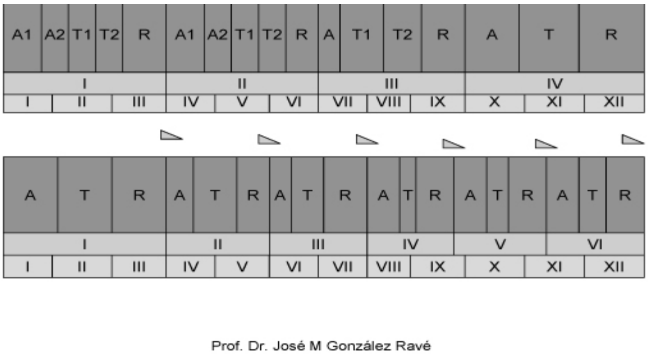


Figure 11. Establishment of several macrocycles per season.

This figure shows how an annual cycle has several macrocycles that run during the year. Moreover, we can obtain longer macrocycles by consecutively placing 2 accumulation mesocycles and 2 transformation macrocycles, achieving precise and longer training combinations.

In this case, we need to include a capacity in each mesocycle, thereby ensuring a longer residual effect. The predominant training types, if we consecutively employ several mesocycles of the same type, could be those proposed by Navarro (2000:155) as established in Table 2:

Mesocycles	Main type of training	Additional objectives
Accumulation 1	Aerobic endurance	Maximum strength General conditioning
Accumulation 2	Maximum strength	Aerobic endurance General conditioning
Transformation 1	Muscular endurance	Aerobic-anaerobic endurance Perfecting the skills
Transformation 2	Aerobic-anaerobic endurance	Strength-resistance Anaerobic endurance Perfecting the skills
Realization	Modelling the competition. Speed capabilities	Anaerobic endurance Competitive skills Tactics

Table 2. Training options with 2 mesocycles of accumulation and transformation.

Finally, the competitions in this model are preferentially located in the mesocycle of implementation and always at the end, hence the situation of competitions affecting the planning design. However, for competitions with less preparation, these can be distributed in the implementation or transformation mesocycles.

Of course, the number of competitions will depend on the type of sport and its level of implementation and popularity and the athletes' current level. Thus, elite athletes must attend more competitions and should therefore have more microcycles.

The ATR model is not exempt from criticism, as stated by Kiely (2010); however, the reply by Issurin (2010) to his critics merely fuels a most interesting discussion on the scientific validity of the ATR model. There are studies that supports its validity, although they are few. The study by Breil et al. (2010) used an ATR model for 11 days (15 intensive interval training sessions) with elite skiers. The skiers who used concentrated loads improved their VO2max by 6.0% ($p<0.01$; men, 7.5%; women, 2.1%), relative peak power by 5.5% ($p<0.01$) and second ventilatory threshold by 9.6% ($p<0.01$). The control group had no changes. Another study that showed improvements in the study parameters was carried out by Nuñez et al. (2008) on a sample of football players. The study employed training blocks with only resistance content or with only strength contents. The authors concluded that aerobic resistance improved in the initial phase of the season because of the training. To increase strength, the number of training session of this type needs to be increased. It is advisable to separate aerobic resistance and strength training to create wider blocks during the last 2 macrocycles. García-Pallarés et al. (2010) performed a comparative study with elite kayaking athletes between an ATR model (13 weeks) and a classical model (23 weeks). The authors concluded that performance was improved in the 2 models. However, the blocks model was more efficient in parameters such as stroke speed and maximum power manifested in the VT2.

Polarized training periodization

This periodization model is conceptualised as the integration and distribution of various intensities of training focused on low and high (thereby polarising the distributions), as established by Stoggl & Sperlich (2014). Based on the concept of distribution of training intensity, whose most representative studies are those by Seiler (2010) and Seiler & Tonnessen (2009), which show how (in the analysis performed during a season) most of the work volume is performed at low intensity (approximately 80%), while the rest is performed at high intensity. Based on this procedure, this periodization model has been articulated around resistance capacity. The review conducted by Stoggl & Sperlich (2015) concluded that polarised periodization was an effective strategy for some elite athletes during certain phases of the season. However, experimental studies that lasted 6 weeks to 5 months showed superior responses with polarised training, especially when comparing models that emphasised the anaerobic threshold with contrasts of high volume-low intensity. This combination can improve resistance performance, with potentially less nerve and hormonal stress, and prevent the typical monotony. Mujika et al. (1995) measured the distribution of training intensity for international swimmers during a whole season based on 5 areas of intensity, which in turn were based on blood lactate levels. Although the swimmers specialised in the 100 m and 200-m events that required approximately 60 s to 120 s, these swimmers swam 77% of the 1150 km completed during a season at an intensity below 2 mM of lactate. The rest was performed at high intensity. The study by Yu et al. (2012) showed positive results using this periodization model in professional skaters. Muñoz et al. (2014) assessed the impact of a polar training distribution compared with a low-intensity training program and a traditional programme in recreational athletes. The study showed improvements in all groups, although the polar training programme provided greater improvements than the low-intensity training. Other studies, such as those by Hydren & Cohen (2015) and Varela et al. (2016), have shown the advantages of this training programme.

The season distribution, according to Stoggi and Sperlich (2014), is performed as follows:

1) Preparation Period.
2) Precompetitive Period.
3) Competitive Period.

Each of these periods distributes the training intensity in very different ways, as shown in Figure 12.

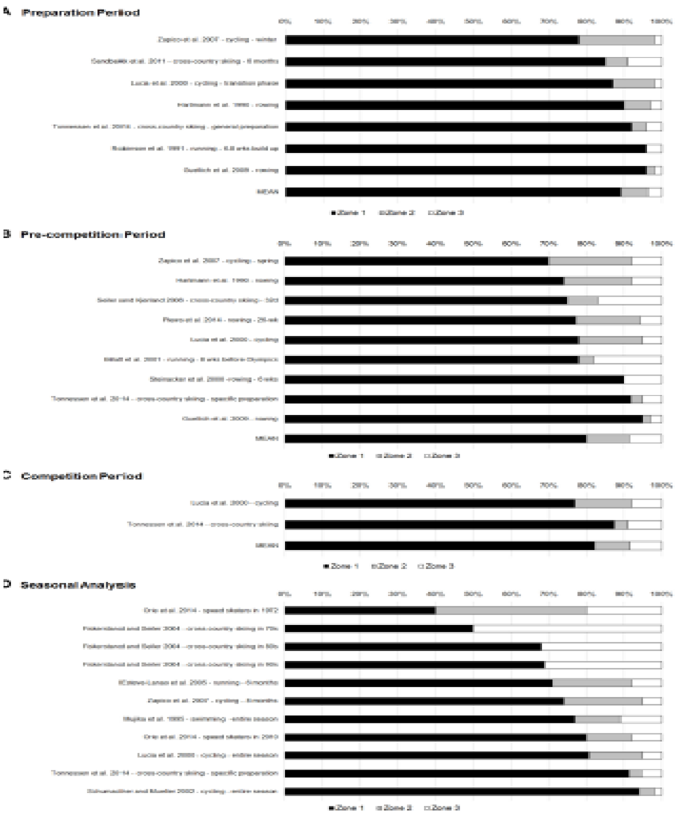


Figure 12. Training intensity distribution in the various periods (Stoggi & Sperlich, 2014).

References

Baker, D. (1994) Periodization the effect on strength of manipulating volume and intensity. J. Strength Cond. Res.; 8: 235-242.

Bompa, T (1999) Periodization. Theory and methodology of training. Human kinetics. Champaign, IL.

Breil FA, Weber SN, Koller S, Hoppeler H, Vogt M.(2010) Block training periodization in alpine skiing: effects of 11-day HIT on VO2max and performance. Eur J Appl Physiol. 2010 Aug;109 (6):1077-86.

Busso, T.; Thomas, L. (2006) Using mathematical modelling in training planning. International J. of Sport Physiol and Performance. 1: 400-406.

Counsilman BE, Counsilman J. (1991) The residual effects of training. J Swim Res 1991; 7: 5-12.

Fleck, S. J. (1999) Periodized strength training: A critical review. J. Strength Cond. Res. 13(1):82–89.

Fry, R.W., Morton, A.R.; Keast, D. (1991) Overtraining in athletes. Sports Medicine 12, 32-65.

García, J.; Navarro, M. y Ruiz, J. (2000). Planificación del entrenamiento deportivo. Madrid. Gymmos.

García-Pallarés J, García-Fernández M, Sánchez-Medina L, Izquierdo M. (2010) Performance changes in world-class kayakers following two different training periodization models. Eur J Appl Physiol. 110(1):99-107.

González Ravé, JM, Arija, A, and Clemente-Suarez, V. (2011) Seasonal changes in jump performance and body composition in women volleyball players. J Strength Cond Res 25(6): 1492–1501.

González Ravé, JM; Juárez, D; Garcia, JM; Navarro, F (2007) Eficacia de la periodización del entrenamiento sobre la potencia máxima. Archivos Medicina del Deporte, 119, 179-186.

Gorostiaga, E. M., C. Granados, j. Ibañez, j. J. Gonzalez-Badillo, and M. Izquierdo.(2006) Effects of an Entire Season on Physical Fitness Changes in Elite Male Handball Players. Med. Sci. Sports Exerc., 38 (2) 357–366.

Granados, C., M. Izquierdo, J. Ibañez, M. Ruesta, E. M. Gorostiaga. Effects of an Entire Season on Physical Fitness in Elite Female Handball Players. Med. Sci. Sports Exerc., Vol. 40, No. 2, pp. 351–361, 2008.

Grosser, M. Brüggemann, P; Zintl, F. (1989) Alto Rendimiento Deportivo: Planificación y Desarrollo. Martínez Roca. Barcelona.

Hernandez Moreno, J (1988) Baloncesto: iniciación y entrenamiento. Paidotribo. Barcelona.

Hoffman, J. (2002) Physiological aspects of sport training and performance. Champaign (IL): Human Kinetics.

Howley ET; Franks, BD (1986) Health/fitness instructor handbook. Humankinetics. Champaign. IL.

Hydren JR, Cohen BS. (2015) Current Scientific Evidence for a Polarized Cardiovascular Endurance Training Model. J Strength Cond Res. Dec; 29(12):3523-30. doi: 10.1519/JSC.0000000000001197.

Issurin, V. (2008) Block Periodization versus traditional training theory: a review. J Sports Med Phys Fitness; 48 (1): 65-75.

Issurin, V; Lustig, G (2004) L´effetto residuo di allenamento. Classificacione, durata e componenti pratiche dell´effetto residuo di allenamento. Sds. Rivista di cultura Sportiva, 60-61, 25-29.

Issurin,V (2010) New horizons for the methodology and physiology of training periodization. Sports Med 2010; 40 (3): 189-206.

Issurin,V; Shkijar, V (2002). la struttura a blocchi dell´allenamento. La concezione della struttura a blocchi dell´allenamento degli atleti de alto livello. Sds. Rivista di cultura Sportiva 56:6-9.

Kell, JR (2011) the influence of periodized resisted training on strength changes in men and women. J Strength Cond Res. 25(3): 735–744, 2011.

Kiely, J (2010) New Horizons for the Methodology and Physiology of Training Periodization Block Periodization: New Horizon or a False Dawn Sports Med 2010; 40 (9): 803-807.

Martin, D; Carl, K; Lehner, K (2001) Manual de metodología del entrenamiento deportivo. Paidotribo. Barcelona.

Matveyev, L.P. (1977) Periodización del entrenamiento deportivo. Instituto Na-

cional de Educación Física y Deportes. Madrid.
Matveyev, LP (2001) Teoría general del entrenamiento deportivo. Paidotribo. Barcelona.
Mujika I, Chatard JC, Busso T, Geyssant A, Barale F, Lacoste L (1995). Effects of training on performance in competitive swimming. Canadian Journal of Applied Physiology 20, 395-406.
Muñoz I, Seiler S, Bautista J, España J, Larumbe E, Esteve-Lanao J. (2013) Does polarized training improve performance in recreational runners? Int J Sports Physiol Perform. 2014 Mar;9(2):265-72. doi: 10.1123/ijspp.2012-0350.
Navarro, F (2000) La controversia actual sobre la planificación del entrenamiento. INFOCOES, 5(2), 55-69.
Navarro, F. (2010) Planificación del entrenamiento y su control. Ed: Cultiva Libros. RFEN. Madrid.
Navarro, F. (2000) Principios del entrenamiento y estructuras de la planificación deportiva. C.O.E. Madrid.
Norris, SR; Smith, DJ (2002) Planning, periodization and sequencing of training and competition: the rationale for a competently planned, optimally executed training and competition program, supported by a multidisciplinary team. In M. Kellmann (ed.) Enhancing recovery. Preventing underperformance in athletes. Champaign: IL. Pp 121-141.
Norris, SR; Smith, DJ (2002) Planning, periodization and sequencing of training and competition: the rationale for a competently planned, optimally executed training and competition program, supported by a multidisciplinary team. In M. Kellmann (ed.) Enhancing recovery. Preventing underperformance in athletes. Champaign: IL. Pp 121-141.
Núñez VM, Da Silva-Grigoletto ME, Castillo EF, Poblador MS, Lancho JL. (2008) Effects of training exercises for the development of strength and endurance in soccer. J Strength Cond Res. 22(2):518-24.
Platonov, VN (2000) El concepto de la periodización del entrenamiento y el desarrollo de una teoría del entrenamiento. INFOCOES, 5(1), 87-93. Traducción de Leitungsport 1/1999.
Plisk, SS; Stone, MH (2003) Periodization strategies. Strength and Conditioning J., 25 (6), 19-37.
Rhea, MR. and Aldeman, BL. (2004) A meta-analysis of periodized versus non-periodized strength and power training programs. Reserch Quarterly for exersice and sport. 75:413-422.
Seiler, K. S., Tonnessen, E. (2009). Intervals, thresholds, and long slow distance: the role of intensity and duration in endurance training. *Sportscience* 13, 32–53.
Seiler, K. S. (2010). What is best practice for training intensity and duration distribution in endurance athletes? *Int. J. Sports Physiol.* 5, 276–291.
Selujanov, VN (1999) La clasificación científica-histórica del concepto de la periodización del entrenamiento y su crítica. INFOCOES, 4(1), 89-91. Traducción de Leitungsport 2/1999.
Seyle, H. (1956)The Stress of Life. New York: McGraw-Hill. 1956.
Stone, MH; O´bryant, HS; Garhammer, J. (1981) A hypothetical model for strength training. J. Sports Med. Phys. Fitness, 21: 342-351.
Stöggl T, Sperlich B(2014) Polarized training has greater impact on key endur-

ance variables than threshold, high intensity, or high volume training. Front Physiol. 4;5:33. doi: 10.3389/fphys.2014.00033.

Stöggl TL, Sperlich B (2015) The training intensity distribution among well-trained and elite endurance athletes. Front. Physiol. 6:295. doi: 10.3389/fphys.2015.00295

Verchoshanskij, Y; Siff, M (2000) Superentrenamiento. Paidotribo. Barcelona.

Verkhoshanski, Y (1990) Entrenamiento deportivo. Planificación y programación. Martínez Roca. Barcelona.

Wathen, D (1994) Periodization: concepts and applications. In Baeche, TR (eds) Essentials of strength training and conditioning. NSCA. Humankinetics. Champaign. IL. pp 459-472.

Wathen, D., T. R. Baechle, and R. W. Earle.(2000) Training variation: Periodization. In: Essentials of Strength Training & Conditioning (2nd. ed.). Baechle and Earle (eds.). Champaign, IL: Human Kinetics. PP. 513–527.

Wathen, D; Roll, F (1994) Training methods and modes. In Baeche, TR (eds) Essentials of strength training and conditioning. NSCA. Human kinetics. Pp 403-415.

Willoughby, DS. (1993) The effects of meso-cycle-length weight training programs involving periodization and partially equated volumes on upper and lower body strength. J. Strength Cond. Res. 7: 2-8.

Yu H(1), Chen X, Zhu W, Cao C (2012) A quasi-experimental study of Chinese top-level speed skaters' training load: threshold versus polarized model. Int J Sports Physiol Perform. 7(2):103-12.

Development of talent of adolescents in Australian sports high schools

Ross Sanders, Rhonda Orr, Chuang-Yuan Chiu, Angus Chard, Claire Tompsett, Jennifer Fleeton, Timothy Davies, Alycia Fong Yan [1]

Introduction

There are seven high schools in NSW designated as 'sports' high schools. They offer a special curriculum to enable students with high potential in specific sports to have additional coaching and talent development opportunities. Entry to the 'sport stream' of these schools is selective and competitive. The students are selected based on their sporting background and interview. The program has been developed by the Discipline of Exercise and Sports Science (ESS) in the Faculty of Health Sciences, The University of Sydney, in response to an approach by the Principals of the sports high schools. Ensuing discussions between two Principals and the sport scientists of ESS identified the following issues to be addressed to achieve the schools' mission of enabling students to fulfil their academic and sporting potential: (i) students sporting careers being affected by injuries which may be prevented through attention to predisposing factors early in their development; (ii) limitations to ongoing success and improvement not being identified and rectified; (iii) students with potential not being recognized and nurtured due to chronological and biological age differences among students in the same age division; (iv) students not selecting, or being streamed into, sports and positions that make the best use of their attributes.

Development of the Program

The program is designed to be longitudinal in nature, addressing the needs of individual students over a five-year period commencing from each student's first year of high school (Yr 7 - age ~13 years) to their penultimate high school year (Year 11 – age ~17). Assessment of their current status in various attributes related to performance is conducted three times per year. This provides a basis for selection of supplementary activities during their training sessions to address their developmental needs.

[1] Discipline of Exercise and Sport Science, Faculty of Health Sciences, The University of Sydney, Sydney, Australia

1. Assessment of Injuries and Injury Risk

Injury in adolescent years may negatively impact longer-term health and wellbeing as well as potential representative and/or professional careers (1, 2). Assessment of injuries and injury risk comprises ongoing injury surveillance and measurement of joint characteristics that are known to be associated with injury. The injury surveillance includes a questionnaire of injury history prior to the time of entry to the program in Year 7 and injury status at that time. Demographic information (age, ethnicity), medical history, medications and supplements and athlete sport-specific characteristics (playing history, playing position, protective gear) was also collected. Ongoing surveillance is achieved through a standardised monitoring process.

Injury was defined as '….any physical or medical condition that occurs during participation in match or training activities that results in a missed match or training participation' (3). Match and training injuries (including concussions) are recorded at each game and training session in a standardised format using the Athlete Injury Surveillance Profile (4). Factors pertaining to injury include:

1) Characteristics
2) Onset
3) Diagnosing/Treating Person
4) Treatment given
5) Injury Follow-up
6) Modified training required and training time and/or match time lost

Presentations are conducted to familiarise sports convenors and coaches to the study objectives and data collection procedures. Sport convenors or coaches complete the injury recording form which records the: body location; type; mechanism; occurrence (date, match vs. training; first vs. second half); environmental conditions (weather, ground, indoor); initial diagnosis; initial treatment (e.g. ice, strapping); treating person; and referrals pertaining to the injury (e.g. hospital, physiotherapist, doctor). To maximise consistency and reduce reporting bias, forms are to be completed as soon as possible after the injury and by the same individual for each sport, where possible.

An injury follow-up form (subsequently completed by the physiotherapist or medical practitioner and sport convenor) documents the: injury diagnosis; further referral (e.g. physiotherapist, diagnostic scans, surgeon); number of modified and/or missed training sessions; and number of missed matches. Injury severity is classified according to the number of matches missed (0 = transient; 1 = mild; 2-4 = moderate; ≥5 = major). Injury incidence calculations (per 1000 player hours) are in accordance with King et al. (5).

The surveillance data are assessed in conjunction with the measurement of joint characteristics including stiffness, mobility, configuration and posture. These have been identified as important in the literature and are described below:

Foot Posture Index (FPI)

The FPI is the gold standard for differentiating and quantifying foot posture. This easily implemented in-field tool considers six different aspects of standing foot posture as seen in Table 1, allowing the clinician to quantifiably differentiate and categorise individual foot postures, as seen in Table 2, from one another. This method can distinguish at risk groups considering biomechanical risk factors that may allow for the prevention and early intervention of musculoskeletal conditions (6-8) and can help to predict dynamic foot function (9). Features the FPI included reliability, implementation simplicity, quantitative scoring related to the complexity of foot function, minimal subjectivity and easy field implementation without needing sophisticated measuring equipment (10). As foot posture measures taken during weight-bearing are more representative of dynamic foot function than non-weight bearing measures (11), the assessment was devised to take place during quiet, double-limb-supported standing. The resulting system, the foot posture index (FPI) considers rearfoot sagittal, frontal and transverse plane positions, as well as midfoot sagittal and transverse plane foot positions (Table 1).

Joint	Plane	Test
Rearfoot	transverse	talar head palpation
	frontal/ transverse	curvature at the lateral malleoli
	frontal	inversion/eversion of the calcaneus
Forefoot	transverse	talonavicular bulging
	sagittal	congruence of the medial longitudinal arch
	transverse	abduction/adduction of the forefoot on the rearfoot

Table 1. The six-item foot posture index (FPI) tests and their relationships to joint and plane of motion

Keenan, Redmond (12) transformed the FPI scores to interval logit scores in accordance with the Rasch model and normal ranges of foot posture were defined for 619 healthy individuals ranging in age from 3—96 years. From these data, a slightly pronated foot posture of +4 was considered healthy, with normal foot posture achieved by the age of eight. Scores either side of the neutral point indicated potentially abnormal and truly abnormal ranges (13) Table 2).

	Truly pathological	Potentially abnormal	Normal range			Potentially abnormal	Truly pathological
	Highly supinated	Supinated	Healthy			Pronated	Highly pronated
	< -2 SD	-2 SD	-1 SD	Mean	+1 SD	+2 SD	> +2 SD
FPI raw score	< -3	-3	+1	+4	+7	+10	> +10

Table 2. FPI scores and their relationship to healthy normal foot posture

The FPI has been subjected to thorough validation. It proved to be an adequately reliable assessment of adults in various clinical settings, with intra-class correlation coefficients (ICC) of 0.62—0.91 (14-17). In children and teenagers aged 5—16 years, inter-rater reliability was almost perfect (Kw = 0.88; (18)). More recently, in children aged 7—15 years, the FPI was found to have good intra-rater reliability using the Portney and Watkins criteria (19) with ICC = 0.93—0.94 (20). The finalised FPI instrument predicted 64 % of the variance in stationary standing foot posture and 41 % of the dynamic walking midstance foot posture (10).

FPI as a Pathology Predictor

The FPI is a valid, reliable, easily-implemented, clinically-relevant descriptive foot posture tool that can distinguish at-risk groups. It can distinguish foot related biomechanical risk factors, which may allow prevention and early intervention of lower limb musculoskeletal conditions. The FPI is sensitive to distinguishing musculoskeletal pathologies with evidence from several populations:

- Naval recruits with a pronated foot postures (FPI ≥ +6) were significantly ($P = 0.002$) more likely to develop medial tibial stress syndrome (MTSS) than recruits with normal (+1 to +5) or supinated (0 to -16) foot postures, with a risk ratio of 1.70 (21).

- Adult participants with highly supinated foot postures reported greater incidence of foot pain (60%) compared to participants with normal foot postures (23 %, FPI 0 to +6; $P = 0.009$). Pressure–time integrals under the whole foot, rearfoot and forefoot were higher than in normal feet ($P < 0.01$). Pressure–time integrals in subjects reporting foot pain were higher than for pain-free subjects ($P < 0.001$). There was a significant correlation between pressure–time integral and foot pain ($r = 0.49$, $P < 0.001$) (6).
- Triathletes with highly supinated foot postures (FPI ≤ -2) had a significantly greater likelihood of overuse injuries during the competition season. Risk of injury occurring in this foot type was 4.3 times greater; $P = 0.013$, than those without (7).
- Adults with chronic plantar heel pain were found to be more likely to have a pronated (FPI ≥ 4) foot posture (OR = 3.7, 95% CI = 1.6 – 8.7, $P < 0.01$) (22).

Function Predictor

- Foot motions of healthy adults aged 18—47 can be predicted during normal walking with the static FPI. In the case of pronated and highly pronated participants (FPI > +6), reduced midfoot frontal plane range of motion was seen in late stance. In supinated and highly supinated participants, less midfoot motion was seen during initial contact and midstance, and altered frontal and transverse plane motions were observed when compared to control participants with normal FPIs (23). Adults ranging from 18—71 years of age displayed a greater lateral centre-of-pressure excursion, correlating with greater supinated foot postures and, conversely, the more pronated the foot posture, the smaller the area of lateral centre-of-pressure excursion. In addition to this, the supinated foot type had a larger centre-of-pressure total excursion area, and the pronated foot type had a smaller centre-of-pressure total excursion area.

Ist MPT Joint Stiffness

First metatarsal phalangeal (1st MPT) joint extension is necessary for healthy foot function (24, 25). Restricted sagittal plane motion, that is, less than 64 ° (26) can be an important predictor of injury (27-29) and foot function (30-32). Using a hand-held goniometer, the sagittal plane axis of the 1st metatarsal and proximal phalanx are determined and measured. Restricted extension (<64 °) or signs of joint derangement (26), including; ‘hard end point’ at maximum extension, dorsal joint lipping with bony growth (exostosis) formation, pain with dorsomedial palpation or valgus deviation greater than 15 ° would be recorded (33, 34). Intra-rater reliability has been determined as 0.99 (35). Inter-rater reliability has with an inter correlation coefficient of 0.95 has been determined (26, 33).

Lunge Test

Restricted ankle dorsiflexion has been identified as a contributing factor in overuse injuries of the lower limb and foot (36, 37) and strong predictor of injury ($p = 0.03$) (38). Normative values have been reported (38). This test has been demonstrated to have an intra-tester reliability of ICC = .98 (SEM = 1.1 °) and an inter-tester reliability of ICC = .99 (SEM = 1.4 °) (39) for adults and for children aged 7-15 years of age ICC = 0.85-0.95.

Prior to determining the ankle lunge measurement, the tibia must be marked for the standardised measuring location. This is done with the participant lying supine. The tibial tuberosity is first isolated and marked. Using a 10 cm ruler a point is marked distal to the tibial tuberosity on the most lateral bony ridge of the anterior tibia. The participant aligns their 2nd toe to a line on the floor to the anterior and heel bisection to the posterior, then places the contralateral leg to a line on the floor and assumes comfortable easy rest position. Placing the test legs corresponding hand on a chair back, for balance, the participant steps forward flexing the test leg in the sagittal plane. The examiner takes care to ensure femoral abduction/adduction is negated as the knee cap flexes over the 2nd toe. The participant flexes and straightens their knee three times before the measure is taken with knee maximally flexed will maintain full heel contact. The examiner aligns the long edge of a digital inclinometer (iPhone 6 or equivalent using the application “iHandy-Level™”) to the most lateral ridge of the anterior tibia with the midpoint of the inclinometer aligned with the existing mark already determined. The angle is measured to the supporting surface and recorded. (22, 39).

Beighton Scale

The Beighton scale is a commonly used valid and reliable clinical measure of generalised joint hypermobility or ligamentous laxity (40, 41) and normative data exists for athletes. Generalised joint laxity was not shown to be significantly elevated in adolescent male athletes (42) but females were found to be significantly more hypermobile than males during puberty (43). Aside from a greater risk of knee injuries in contact sports among those with hypermobility, there is currently insufficient evidence associating hypermobility with injury risk (44). The Beighton scale (41) is used to ascertain the presence of joint hypermobility at the wrist, fifth metacarpal phalangeal joint, elbow, knee (all bilateral and non-weight-bearing) and the lumbo-sacral spine (forward flexion, in stance). The Beighton scale yields a score related to static postures of the upper limbs, and hips, whereby the arbitrary cut-off of 5/9 or greater for females and 4/9 for males indicates joint hypermobility (41).

Lower Limb Assessment Scale

Since the Beighton score is largely focused on the upper limbs, the Lower Limb Assessment scale was developed to assess lower limb hypermobility (45). This scale includes 12 items, with separate scores for the right and left legs (45). A majority of the items require passive manipulation of the joint to assess the joint laxity. The scale is valid and reliable and was able to predict generalised hypermobility in a greater percentage of people than the Beighton Scale (45). Clinically, both LLAS and Beighton Scale are used together. In children, there is no significant difference between right and left legs prior to puberty (45), therefore, it is possible to test one leg if expediency is required.

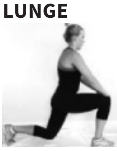
2. Identifying and Improving Attributes Related to Success

The school coaches work to develop the sport specific skills through their various skills practices. However, development of these skills and their execution in game situations can be affected by various limitations. To address the issue of 'limitations to ongoing success and improvement not being identified and rectified' we have structured an assessment and remediation program around several categories of potential limitations including 'basic human movements', 'strength and conditioning', 'balance', and 'flexibility'.

Basic Human Movements

Research has revealed that despite years of practice and development of sport specific skills, ongoing performance levels and skill development may be affected by poor development of basic human movements (BHM) in both primary and high school athletes (46). These are considered the pre-requisite essentials underpinning control of more complex sports skills such as running, jumping, catching, striking and throwing skills (47, 48). Deficits in BHMs are often unnoticed and unexpected among those who, to all appearances, are ‘sporty’ and well-co-ordinated.

Sport training with appropriate conditioning reduces risk of injury in young athletes (49). Documented intrinsic risk factors have suggested neuromuscular control (50), core instability (51), and contralateral muscular imbalances (52) are related to injury risk. Compensatory movement patterns utilized to achieve complex skill performance are often overlooked in the young competitive population. However, these inefficient movement systems may reinforce poor biomechanical movement patterns during typical activities, resulting in injury (53). The BHM assessment tool is used to detect compensatory movement patterns and core instability in young athletes and can be used for early intervention to reduce injury risk. To assess the development of BHMs, participants demonstrate a squat, lunge, push up, pull up, hinge (bend), rotation and brace (plank) which are scored according to the criteria illustrated in Figure 1 (54).

SQUAT 	Weight evenly distributed between the legs during ascent and descent. Gaze remain forwards or up throughout. Heels remain in contact with the ground throughout. Spine remains in a parallel position with the shins. Knees reach at least parallel with the hips.
LUNGE 	Foot lands directly in front of the hip. Knee tracks over the foot while the shin remains vertical. Hips remain in line horizontally. Smooth and balanced transition between steps. Back foot remains facing the front. Trunk remains upright throughout the lunge.
HINGE 	Weight distributed evenly between sides throughout the movement. Spine maintains a natural curve during the ascent and descent. Shoulder blades are retracted to maintain natural curve of upper back. Head remains in neutral alignment with the spine. Knees remain at a fixed angle, i.e. do not bend/straighten throughout the movement.
ROTATION 	The feet and knees remain facing the front. Body remains vertically aligned. Shoulders remain in horizontal alignment throughout rotation. Rotates at least 90° each side. Spine maintains neutral alignment.

PULL UP 	Weight evenly distributed between the hands during the ascent and descent. Shoulders remain square during the ascent and descent. Trunk maintains a rigid position throughout the movement. Trunk maintains a rigid position throughout the movement. Chest is pulled until body is horizontal to the ground.
PLANK 	Shoulders are horizontally aligned. Weight is evenly distributed between sides. Shoulders align with the trunk through to the toes. Head is held in line with the spine. Correct position is held for at least 45 s.
PUSHUP 	Weight evenly distributed between the hands during the ascent and descent. Shoulders remain square during the ascent and descent. The elbows flex to at least 90° to the ground at the bottom of the movement. Spinal column maintains straight alignment from the base of the neck through to the knees.

Figure 1. Description of Basic Human Movements.

Strength and Conditioning

Counter Movement Jump

The counter movement jump (CMJ) is a vertical jump for maximum height in which a counter movement (flexion of the hips and knees immediately prior to the jump) is permitted. The CMJ is a widely used field-based test to assess muscular power of the lower body (55). Studies have shown that performance in the vertical jump test is able to distinguish between athletes that compete at various levels in a variety of sports such as Australian Rules football (56, 57) and rugby league (58, 59). The performance of CMJ can be assessed using a contact platform (e.g. SmartJump; Fusion Sport, Coopers Plains, Australia) to determine the time between take-off and landing (i.e. flight time) from which the height jumped is estimated using the formula for projectile motion. An alternate method of assessing jump height is the Vertec (Questek) measuring device, which assesses vertical jump height by measuring the difference between the athlete's standing reach height and their maximal jump and reach height.

Portable contact platforms such as SmartJump (Fusion Sport, Coopers Plains, Australia) have been shown to produce reliable measurements with errors of no more than ~ 3.0 % for countermovement jumps (60). To improve reliability of CMJ height assessment it is recommended that all athletes are provided with thorough familiarisation and complete a minimum of three trials, with the maximal CMJ height reported. In the case of the Vertec measuring system, a separate familiarisation session is recommended (55). Intrasession reliability of the countermovement jump height measured with the Vertec device has been found in females ICC = 0.89, SEM = 2.1 cm, CV 6.9 %; and in males ICC = 0.94, SEM = 2.2cm, CV = 5.5 % (55) Intersession reliability for both males and females combined ICC = 0.80, SEM = 2.7 cm, CV = 8.6 % (55).

Medicine Ball Chest Throw

The medicine ball chest throw is a simple field test to measure upper body power (61). Upper body power is an important aspect in many sports, from throwing based field sports such as javelin to fending tackles in rugby league. The student throws a 3 kg medicine ball while sitting on an upright bench with feet flat on the floor, knees at 90 º flexion, while their head, shoulders, and lower back remains against the backrest of the bench. Each student has two practice attempts for familiarisation and warm up prior to performing three trials with 15 s of recovery between trials. The score is the greatest distance thrown of the three throws measured to the nearest 0.1 m.

Garrido, Marinho (62) found that this test had a strong correlation explaining 25-49 % of the variance in swim times of national level youth swimmers. The medicine ball chest throw has very high test-retest reliability with an ICC of 0.92 (62).

Sprint Speed and Acceleration

Sprint speeds are used alongside other measures such as leg power and agility to distinguish athletic talent (63). Sprint testing is commonly included in the test battery for athletes involved in team field-based sports such as rugby league, rugby union, Australian Rules Football and basketball (64-67). It is assumed that a distance of 10 m can be used to assess an individual's ability to accelerate, whereas maximal velocities are achieved at 20-40 m (64, 65, 67).

Subjects perform maximal effort sprints over 20 m and are timed at 5 m, 10 m and 20 m. The timings can be obtained using timing gait systems such as 'SmartSpeed' (Fusion Sport, Coopers Plains, Australia). After a standardized warm-up (including jogging, dynamic range of motion exercises, and submaximal sprints), subjects perform three maximal sprints with a 3 min rest between attempts. Subjects commence each sprint from a 2-point standing start (dominant foot placed anteriorly of the non-dominant foot, ~ 30 cm apart, the arms do not make contact with the ground) 30 cm behind the first timing gate. Subjects commence in their own time and sprint at their maximum pace through the 20m timing gate and are told to continue running through markers situated ~ 2 m beyond the 20 m timing gate before decelerating. The best of the three times is used as their total 20 m sprint score, timed to the nearest 0.01 s, with split times from 0-5m and 0-10m used to determine acceleration ability (65). Good reliability has been shown with sprint times for 10, 20, and 40 m in semi-professional rugby league players (typical error ranging from 1-2 %) (68).

505 Change of Direction Speed Test

The ability to repeatedly sprint and change direction while sprinting is a determining factor of performance in many field and court sports including rugby, field hockey, tennis, basketball and soccer (69). Scanlan, Humphries (70) described agility performance as dependent on not only the physical aspects of an athlete (technique, linear speed, muscular qualities and morphology), but also perceptual and decision making components (visual scanning, situational knowledge, pattern recognition and anticipation). Thus to be considered a true assessment of agility performance a field based test must be an open skill, requiring an unrehearsed reaction to a stimulus, as well as a change in speed or direction (69). Within the time constraints of the current program, where assessments were carried out within normal class times necessitating the assessment of up to 30 athletes within as little as 36 min, an assessment involving the perceptual and decision making aspects of agility was not possible. Thus the 505 change of direction speed (CODS) test was used as it is a time-efficient, valid and reliable test to assess the neuromuscular and biomechanical aspects of an athlete’s ability to rapidly change direction (71, 72).

Following a standardised warm up as described above, athletes start in a 2-point standing start position and sprint forward through timing gates placed at 10m to a marked turning line at 15 m. Athletes plant their foot on the turning line (using their preferred foot), turn 1800 and sprint the 5 m back through the timing gates. Participants should be allowed three practice trials, followed by three timed trials with 3 min rest between each trial. The fastest of the three trials, recorded to the nearest 0.01 s, is used for analysis. Male and female combined ICC = 0.88, SEM = 0.06 s, CV = 2.40 % (72).

Multistage 20 m Shuttle Run Test

The maximal multistage 20 m shuttle run test (MST), commonly referred to as the 'beep' test, is a field test commonly used to estimate maximal oxygen uptake (VO_{2max}). The MST is comprised of 23 levels, with each level lasting ~ 1 min (73). The starting speed is 8.5 km/hr, increasing by 0.5 km/hr at each level thereafter. A participant's score is the last level attained prior to failing to reach the marker before the 'beep' on two successive occasions, or when participants reach volitional fatigue.

Strong correlations have been found (r=0.92) between MST performance and VO_{2max} as measured in a laboratory. Flouris, Metsios (74) developed an equation to predict $V0_{2max}$ from MST scores, incorporating data collected via indirect calorimetry while subjects performed the MST thus improving the efficacy of this test compared to earlier prediction models. Standard error of the estimate using this equation was found to be 1.9 $ml.kg^{-1}.min^{-1}$.

$EQ_{TT}\ VO_{2max} = (MAS \times 6.65 - 35.8) \times 0.95 + 0.182$

(EQ_{TT} = equation to predict treadmill test VO_{2max}; MAS = maximal attained speed in the MST (i.e. final shuttle speed)) (74).

VO_{2max} is an important measure in sports performance, as many sports require a minimum threshold of aerobic capacity for performance at an elite level (59, 75, 76). Strong correlations have been found between MST performance and match performance parameters (e.g. sprinting, total distance covered etc.) in national soccer players (77). The MST has been found to be a reliable test for both children (r = 0.89) and adults (r = 0.95) (78).

Yo-Yo Intermittent Recovery Test level 1 (Yo-Yo IR1)

The Yo-Yo Intermittent Recovery test level 1 (Yo-Yo IR-1) is a measure of sport-specific aerobic endurance and is related to an athlete's ability to perform prolonged, high intensity intermittent running as required for many field-based team sports such as Rugby League (79) and Rugby Sevens (80). It is more sensitive in discriminating between different levels of athletes and in evaluating the results of training interventions than $V0_{2max}$ and is a more accurate predictor of on-field performance (80). Following a standardised warm up, athletes perform two 20m runs back and forth at a progressively increasing speed, controlled by a series of audible signals played over a portable sound-system. Between each running bout players have a 10-second active rest period consisting of 2 x 5 m of jogging 'out and back' around a marker. The total distance covered by each athlete is recorded as their score (79).

Using the Yo-Yo IR-1, Deprez, Coutts (81) were able to discriminate between elite, sub-elite, and recreational youth soccer players aged between 11-17 years. Intersession reliability for U13, U15 and U17 age groups were ICC = 0.82, 0.85 and 0.94 with CV = 17.3 %, 16.7 % and 7.9 %, respectively. Age-related normative data are available for elite and non-elite youths (81).

Flexibility

Sit and Reach Test

The sit and reach test is used to determine hamstring and lower back flexibility (82) and is a common field-based assessment (83). Lack of hamstring muscle extensibility has been shown to reduce the mobility of the pelvis (84), which can increase the susceptibility of individuals to musculoskeletal injuries (85, 86).

Figure 2. Demonstration of the Sit and Reach Test using the Flex-Tester® (Novel Products Inc., USA)

The testing apparatus used was the Flex-Tester® (Sit and reach) (Novel Products, Inc., USA). Scale three (AAHPERD) was used to measure the reach distance. This sets the feet nine inches away from the zero on the scale. High reliability has been found for the sit and reach test (4.48 % typical error; 0.84 % change in the mean, 0.95 ICC) by Ayala et al., 2011. Following a set dynamic warm up, the participant sits on the floor with knees straight and feet pressed firmly against the box and medial foot alignment vertical with ankles at 90°. With the arms reaching forward, one hand placed on top the other, and palms faced down the participant reaches forward in one smooth motion, holding the final reach position for 2-3 s while the distance is recorded (87) (Figure 2). Two trials are performed with 10-15 s between trials. The average of the two trials is recorded.

Balance

Foot Lift Test

The foot lift test is a measure of static balance, and has good test-retest reliability (Pearson's R=0.78; $ICC_{2,1}$ = 0.73, 95 % CI 0.40-0.89) (88). Results of the foot lift test have been associated with chronic ankle instability and thus a risk for ankle injuries like ankle sprains (88, 89). The participant stands on one leg with the contralateral foot touching the calf, hands on hips and then closes the eyes. As soon as the eyes close the participant must maintain their single leg stance for 30 s. The number of times any part of the foot lifts of the ground, the person takes a step, and for each second the non-supporting leg is in contact with an error is recorded. If the participant opens their eyes then the trial does not count (88). Two trials are performed and the score is the number of errors in the trial with the smaller number of errors (89).

Anthropometry

Anthropometric tests provide information regarding a player's body dimensions, shape, and body composition as well as an estimation of his or her adult height. The players are tested in close-fitting shorts and sports tops (for female subjects).

Stature

Stature is one of the characteristics related to suitability for different sports and positions and is essential in adult height prediction (90) and in understanding body size and shape (e.g. somatotype scoring (91)). Body size and shape has been found to be related to sports performance (92). For example, being tall and slender is important in swimming as it effects the hydrodynamic resistance encountered by the swimmer (93) while short stature is an advantage in gymnastics to minimise rotational inertia (94). Thus, stature is an important factor in talent identification, athlete selection and sports development (95). Further, stature and somatotype are associated with suitability for different sports and positions (91, 96) and are strong determinants of the best playing position in sports such as AFL, basketball, netball, soccer, field hockey, rugby league and rugby union.

Stature is measured using the 'self-stretch stature method' with a height scale or stadiometer which is adapted from the traditional stretch stature method (97). The participant stands against a vertical wall or stadiometer, touching the wall with the heels, buttocks, and back with heels together. The head is aligned so that the upper border of the ear opening and the lower border of the eye socket are on a horizontal line. The participant is instructed to stretch upward and to take and hold a full breath. The headboard of the stadiometer is moved downwards until it firmly touches the vertex of the head. The measurement of stature is taken in mm at least two times for each subject. Reliability of stature should be within 1 % (98).

Body Mass

Body mass is part of the assessment of characteristics related to suitability for different sports and positions. It is used in combination with stature and girths to determine body composition. It is also used in combination with age, stature and sitting height to predict adult height. Participants step onto clinical scales graduated to 0.1 kg. At least two trials are recorded. Reliability of body mass should be less than 1 % (98).

Girths

Girths of the neck, waist, and hips are measured as part of the assessment of characteristics related to suitability for different sports and positions. Girths are used in combination with stature and body mass to determine body composition. Anatomical landmarks are identified by palpation by a certificated anthropometrist. A tape measurement is taken by following the rules of International Society for the Advancement of Kinanthropometry (97). Each girth measurement is taken in mm at least two times. Reliability of girth measurements should be less than 1 % (98).

Body Composition

Body composition, the quantity of fat as a percentage of body mass, is estimated by a formula (99, 100) that includes stature, body mass, and girths collected from anthropometric tests. Body composition is related to sport performance (101). From a biomechanical aspect, body fat masses cause extra energy consumption and has a negative impact on sport performance (102, 103). Given two players with the same body mass, the one with lower body fat percentage should generally be able to sustain movement at a higher level and for a longer period than the one with higher body fat percentage. In addition, Bahr and Krosshaug (104) indicated that body composition may be a factor which influences the risk of sports injury.

Nutrition Assessment

Nutrition assessment is conducted in this cohort to assess different categories of food intake in adolescent athletes in order to monitor the dietary consumption patterns that may impact performance in their sport. Adequate energy intake is essential for adolescent athletes to support proper growth, maturation and development with possible increased intake to match exercise training and competition requirements. Dietary patterns and hydration strategies should reflect their daily exercise demands. Adolescence is a period in the lifespan that can present challenges to appropriate eating patterns and food selection. In particular, poor dietary habits can limit performance by affecting energy reserves, muscle and bone development, and body composition. Depending on the sport and playing position, players can have too low or too high percentage of fat. For example, some body fat is desirable for swimmers as it assists buoyancy and body alignment when swimming. Rugby props need bulk and strength and benefit from having a higher percentage of fat than players in other positions. However, too much fat reduces their speed and endurance in open play.

The Students As Lifestyle Activists (SALSA) Questionnaire is a short, straightforward questionnaire for use in adolescents where individual items have been validated (105-108). The SALSA Questionnaire estimates daily consumption of breakfast, fruit, vegetables, water, sugary drink intake (i.e. fruit juice, soft drink, sport drinks, cordial, and energy drinks), and intentions of future consumption of these items. In addition there are simple measures of daily physical and sedentary activities and recreational screen time. The SALSA Questionnaire has been modified from the Short Food Frequency Questionnaire (SFFQ) (109). The SFFQ was reported to have fair to moderate validity and moderate to good reproducibility in primary school children aged 10-12 years. Validity and reliability studies of the SALSA questionnaire are currently being conducted.

3. Students with potential not being recognized and nurtured due to chronological and biological age differences among students in the same age division.

Age

Age is calculated in days from dates of birth obtained in a questionnaire completed by parents. This chronological age is then used in combination with stature and sitting height to predict adult stature. Age is essential in adult height prediction (90).

Biological Age and Adult Height Prediction

Adult height prediction (AHP) provides an estimate of the final stature and may be related to young athletes' potential in particular sports. Thus, AHP is widely used for talent identification, athlete selection and sports development (95).

It is also important for coaches to understand the effects of early and delayed maturation on team selection and playing position selection. For example, players who mature early, being taller than peers, may be trained as forwards in basketball or lineout jumpers in rugby but may not be appropriate for those positions as adults due to reaching their final stature being less than later maturing peers. Similarly, those who mature later than peers miss opportunities due to their smaller stature, mass, and muscle development. This is particularly the case where stature, mass, and muscularity are important, for example in rugby league and rugby union. It is well known that swimmers who mature early have an advantage over later maturing peers due to resistance being related to body length and propulsion also being aided by long limbs. Trainability, for example muscle development, aerobic and anaerobic capacity, increases with biological age into adulthood.

Additionally, team selection is biased towards the 'big kids', particularly in sports where size confers an advantage. Indeed, this disadvantages those who mature late as well as those whose birthday falls close to the cut-off of the age division. Thus, those who are biologically or chronologically disadvantaged may miss the opportunity to play at a higher level and to enter the 'development pathway' despite having good potential and skill development. A further adverse possibility is that athletes with potential who cannot maintain performance relative to peers due to late maturation become discouraged. Indeed, this has been recognised as a major cause of 'dropout' (110).

In this talent development program, the prediction equations of Sherar, Mirwald (90) are applied to estimate AHP and also to classify individuals as 'early', 'average' or 'late' in terms of their stage of maturation relative to chronological age. The estimates are based on the ratio of sitting height to standing height which changes with maturation due to the difference in timing of lower limb and trunk growth (lower limb growth precedes trunk growth during adolescence).

Sitting Height

The approach for measuring sitting height is adapted from the traditional method (97). To determine sitting height, players are seated on a measuring box or level platform with their hands resting on their thighs. The player is then instructed to take and hold a deep breath and while keeping the head in the Frankfort plane the measurer applies gentle upward lift through the mastoid processes. The head board of the stadiometer is placed firmly down on the vertex, compressing the hair as much as possible. The measurement of sitting height is taken in mm at least two times. Reliability of sitting height should be less than 1 % (98).

4. Students not selecting, or being streamed into, sports and positions that make the best use of their attributes.

In addition to the effects of biological age and anthropometric variables there are many other factors that affect an individual's choice of sport and playing position. In selecting sports, children are influenced by parents, peers, teachers, and others. Many will take up the sport that their parents played or that their friends play. Knight (111) summarised the influence of parents, siblings, and coaches, on 'starting sport', 'progressing in sport', and 'excelling in sport' indicating the relative influences of each of these by the thicknesses of the lines in a diagram. These influences commonly dominate the selection of a sport despite, in many cases, the individual having attributes that would be better suited to a different sport.

The measurement of attributes of individuals in this program, and the consequent comparisons with norms of elite performers in particular sports, may enable identification of potential in a sport other than the one in which they are currently engaged. For example, a gymnast who is destined to become taller than those in the range of successful performers may be encouraged to take up a sport which uses many of the attributes already developed, for example, dance. Similarly, within a sport, an athlete might be identified as having potential to play in a position that is more suited to their set of attributes. For example, a large and muscular rugby player who is fast and has explosive power may be better suited to being a 'blockbusting' winger than a forward where the muscles, although strong for short bursts of activity, are not suited to enduring long periods of repeated scrummaging.

How the Program will Contribute to Optimising Sports Performance in the Future

The program is yielding a large amount of data that are both age specific for chronological age as well as biological age. From these data, norms are determined which provide potential sports persons with realistic targets to which they can aspire and a means of assessing their progress towards elite level. The norms can be used as generic to all sports and also for specific sports and playing positions. Having chronological age and biological age references norms will help coaches and selectors to recognise, and continue to develop, potential despite current performances being below those of early maturing peers. This will help to reduce 'dropout' and those with potential 'slipping through the cracks'. The data will also support initiatives to organise competition categories based on biological, rather than chronological age or on the basis of anthropometric compatibility, for example, weight division for youth rugby league and rugby union.

Ongoing analysis of the results will help identify correlations between variables that could be associated with sport performance. Predictors of injury can also be identified through ongoing injury surveillance and repeated testing of these suggested variables. Currently the database is being built from the seven sports high schools in NSW. However, there is potential to combine these with data from other sources and from other researchers. A large global data base that is available to athletes and scientists internationally is an ultimate goal and realistic vision given the modern technological capacity for information storage and access.

Conclusion

The program described in this paper is being applied successfully in NSW Sports High Schools. The long term goal is to grow the program to involve other schools and to build a large data base that provides motivational targets for adolescents aspiring to fulfil their sporting potential. Normalisation by biological age may reduce the incidence of 'drop-out' and lost talent. Replication of the program by others may enable merging of data to provide a larger picture of adolescent sport development across broad geographical, cultural, and international regions.

Acknowledgments

The authors would like to acknowledge the support and intellectual input of the Principals of Westfields Sports High School, Roger Davis, and Endeavour Sports High Schools, James Kozlowski, and their sports directors Alex Larkin and Dave Davids respectively. We also acknowledge the cooperation and enthusiasm of the staff and coaches of both schools. These are essential for the success of the program.

References

1. Gabbe BJ, Bailey M, Cook JL, Makdissi M, Scase E, Ames N, et al. The association between hip and groin injuries in the elite junior football years and injuries sustained during elite senior competition. British Journal of Sports Medicine. 2010;44(11):799-802.
2. Grimmer KA, Jones D, Williams J. Prevalence of adolescent injury from recreational exercise: an australian perspective. Journal of Adolescent Health. 2000;27(4):266-72.
3. Hodgson L, Gissane C, Gabbett TJ, King DA. For debate: consensus injury definitions in team sports should focus on encompassing all injuries. Clinical Journal of Sport Medicine. 2007;17(3):188-91.
4. Orr R, Cheng HL. Incidence and characteristics of injuries in elite Australian junior rugby league players. Journal of science and medicine in sport. 2016;19(3):212-7.
5. King DA, Gabbett TJ, Gissane C, Hodgson L. Epidemiological studies of injuries in rugby league: Suggestions for definitions, data collection and reporting methods. Journal of Science and Medicine in Sport. 2009;12(1):12-9.
6. Burns J, Crosbie J, Hunt A, Ouvrier R. The effect of pes cavus on foot pain and plantar pressure. Clinical Biomechanics. 2005;20(9):877-82.
7. Burns J, Keenan AM, Redmond A. Foot type and overuse injury in triathletes. J Am Podiatr Med Assoc. 2005;95.
8. Yates B, White S. The incidence and risk factors in the development of medial tibial stress syndrome among naval recruits. The American Journal of Sports Medicine. 2004;32(3):772-80.
9. Buldt AK, Levinger P, Murley GS, Menz HB, Nester CJ, Landorf KB. Foot posture is associated with kinematics of the foot during gait: A comparison of normal, planus and cavus feet. Gait & Posture. 2015;42(1):42-8.
10. Redmond AC, Crosbie J, Ouvrier RA. Development and validation of a novel rating system for scoring standing foot posture: The Foot Posture Index. Clinical Biomechanics. 2006;21(1):89-98.
11. McClay I. Report of ‘‘Static and dynamic classification of the foot’’meeting, Annapolis, Maryland, May 2000. Journal of Orthopedic and Sports Physical Therapy. 2001;31(3):158.
12. Keenan A-M, Redmond AC, Horton M, Conaghan PG, Tennant A. The Foot Posture Index: Rasch analysis of a novel, foot-specific outcome measure. Arch Phys Med Rehabil. 2007;88(1):88-93.
13. Redmond AC, Crane YZ, Menz HB. Normative values for the Foot Posture Index. J Foot Ankle Res. 2008;1:6.
14. Evans AM, Copper AW, Scharfbillig RW, Scutter SD, Williams MT. Reliability of the foot posture index and traditional measures of foot position. J Am Podiatr Med Assoc. 2003;93(3):203-13.
15. Noakes H, Payne C. The reliability of the manual supination resistance test. J Am Podiatr Med Assoc. 2003;93(3):185-9.

16. Payne C, Oates M, Noakes H. Static stance response to different types of foot orthoses. J Am Podiatr Med Assoc. 2003;93(6):492-8.
17. Yates B, White S. The incidence and risk factors in the development of medial tibial stress syndrome among naval recruits. Am J Sports Med. 2004;32:772 - 80.
18. Morrison S, Ferrari J. Inter-rater reliability of the Foot Posture Index (FPI-6) in the assessment of the paediatric foot. Journal of Foot and Ankle Research. 2009;2(1):26.
19. Portney L. G.; Watkins, M., P.:"Foundations of Clinical Research ". Prentice-Hall, New Jersey; 2000.
20. Evans A, Rome K, Peet L. The foot posture index, ankle lunge test, Beighton scale and the lower limb assessment score in healthy children: a reliability study. Journal of Foot and Ankle Research. 2012;5(1):1.
21. Yates B, White S. The Incidence and Risk Factors in the Development of Medial Tibial Stress Syndrome among Naval Recruits. American Journal of Sports Medicine. 2004;32(3):772-80.
22. Irving DB, Cook JL, Young MA, Menz HB. Obesity and pronated foot type may increase the risk of chronic plantar heel pain: a matched case-control study. BMC Musculoskeletal Disorders. 2007;8(1):41.
23. Buldt AK, Levinger P, Murley GS, Menz HB, Nester CJ, Landorf KB. Foot posture is associated with kinematics of the foot during gait: A comparison of normal, planus and cavus feet. Gait and Posture. 2015;42(1):42-8.
24. Bojsen-Møller F. Calcaneocuboid joint and stability of the longitudinal arch of the foot at high and low gear push off. Journal of Anatomy. 1979;129(Pt 1):165-76.
25. Hicks JH. The mechanics of the foot: II. The plantar aponeurosis and the arch. Journal of Anatomy. 1954;88(Pt 1):25-30.1.
26. Zammit GV, Munteanu SE, Menz HB. Development of a diagnostic rule for identifying radiographic osteoarthritis in people with first metatarsophalangeal joint pain. Osteoarthritis and Cartilage. 2011;19(8):939-45.
27. Clough JG. Functional Hallux Limitus and Lesser-Metatarsal Overload. Journal of the American Podiatric Medical Association. 2005;95(6):593-601.
28. Dananberg H. Gait style as an etiology to chronic postural pain. Part II. Postural compensatory process. Journal of the American Podiatric Medical Association. 1993;83(11):615-24.
29. Menz HB, Morris ME, Lord SR. Foot and ankle risk factors for falls in older people: a prospective study. J Gerontol A Biol Sci Med Sci. 2006;61.
30. Bevan L, Harradine P, Durrant B. The effect of temporary immobilisation of the 1st metatarsophalangeal joint upon in-shoe gait analysis parameters: a preliminary study. Br J Podiatr. 2004;7:54.
31. Dubbeldam R, Nester C, Nene AV, Hermens HJ, Buurke JH. Kinematic coupling relationships exist between non-adjacent segments of the foot and ankle of healthy subjects. Gait & Posture. 2013;37(2):159-64.
32. Lafuente G, Munuera PV, Dominguez G, Reina M, Lafuente B. Hallux Limitus and its relationship with the internal rotational pattern of the lower limb. Journal of the American Podiatric Medical Association. 2011;101(6):467-74.
33. Hopson M, McPoil T, Cornwall M. Motion of the first metatarsophalangeal joint. Reliability and validity of four measurement techniques. Journal of

the American Podiatric Medical Association. 1995;85(4):198-204.
34. Grady JF, Axe TM, Zager EJ, Sheldon LA. A retrospective analysis of 772 patients with Hallux Limitus. Journal of the American Podiatric Medical Association. 2002;92(2):102-8.
35. McPoil TG, Cornwall MW. Relationship Between Three Static Angles of the Rearfoot and the Pattern of Rearfoot Motion During Walking. Journal of Orthopaedic & Sports Physical Therapy. 1996;23(6):370-5.
36. Hughes LY. Biomechanical analysis of the foot and ankle for predisposition to developing stress fractures. Journal of Orthopaedic & Sports Physical Therapy. 1985;7(3):96-101.
37. Warren BL, Jones CJ. Predicting plantar fasciitis in runners. Med Sci Sports Exerc. 1987;19(1):71-3.
38. Baumbach SF, Braunstein M, Seeliger F, Borgmann L, Böcker W, Polzer H. Ankle dorsiflexion: what is normal? Development of a decision pathway for diagnosing impaired ankle dorsiflexion and M. gastrocnemius tightness. Archives of Orthopaedic and Trauma Surgery. 2016;136(9):1203-11.
39. Bennell K, Talbot R, Wajsweiner H, Techovanich W, Kelly DH, Hall AJ. Intrarater and Inter-rater reliability of a weight-bearing lunge measure of ankle dorsiflexion. Aust J Physiother. 1998;44.
40. Boyle KL, Witt P, Riegger-Krugh C. Intrarater and interrater reliability of the Beighton and Horan joint mobility index. Journal of Athletic Training. 2003;38(4):281-5.
41. van der Geissen LJ, Liekens D, Rutgers KJ, Hartman A, Mulder PG, Oranje AP. Validation of Beighton score and prevalence of connective tissue signs in 773 Dutch children. J Rheumatol. 2001;28.
42. Rajeb A, Whiteley R. Beighton scoring of joint laxity and injury incidence in athletic adolescent males. British Journal of Sports Medicine. 2014;48(7):653-.
43. Quatman CE, Ford KR, Myer GD, Paterno MV, Hewett TE. The effects of gender and pubertal status on generalized joint laxity in young athletes. Journal of Science and Medicine in Sport. 2008;11(3):257-63.
44. Pacey V, Nicholson LL, Adams RD, Munn J, Munns CF. Generalized joint hypermobility and risk of lower limb joint injury during sport. The American Journal of Sports Medicine. 2010;38(7):1487-97.
45. Ferrari J, Parslow C, Lim E, Hayward A. Pediatric rheumatology joint hypermobility: The use of a new assessment tool to measure lower limb hypermobility. Clin Exp Rheumatol. 2005;23(413):20.
46. Tompsett C, Burkett B, McKean M. Comparing performances of fundamental movement skills and basic human movements: a pilot study. Journal of Fitness Research. 2015;4.
47. Giles K, Penfold L, Giorgi A. A guide to developing physical qualities in young athletes. Queensland, Austrailia: Movement Dynamics Pty Ltd. 2005.
48. Tompsett C, Burkett B, McKean M. Development of physical literacy and movement competency: A literature review. Journal of Fitness Research. 2014;3(2):53-74.
49. Myer GD, Faigenbaum AD, Ford KR, Best TM, Bergeron MF, Hewett TE. When to initiate integrative neuromuscular training to reduce sports-related injuries in youth? Current sports medicine reports. 2011;10(3):155-66.

50. Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. Journal of Strength and conditioning Research. 2005;19(1):51.
51. Leetun DT, Ireland ML, Willson JD, Ballantyne BT, Davis IM. Core stability measures as risk factors for lower extremity injury in athletes. Medicine & Science in Sports & Exercise. 2004;36(6):926-34.
52. Nadler SF, Malanga GA, Feinberg JH, Prybicien M, Stitik TP, DePrince M. Relationship between hip muscle imbalance and occurrence of low back pain in collegiate athletes: a prospective study. American journal of physical medicine & rehabilitation. 2001;80(8):572-7.
53. Chorba RS, Chorba DJ, Bouillon LE, Overmyer CA, Landis JA. Use of a functional movement screening tool to determine injury risk in female collegiate athletes. North American Journal of Sports Physical Therapy : NAJSPT. 2010;5(2):47-54.
54. Tompsett C, Cobley S. Basic Human Movement Assessment: User Guidelines. Sydney, Australia: The University of Sydney; 2016.
55. Nuzzo JL, Anning JH, Scharfenberg JM. The Reliability of Three Devices Used for Measuring Vertical Jump Height. The Journal of Strength & Conditioning Research. 2011;25(9):2580-90.
56. Bilsborough JC, Greenway KG, Opar DA, Livingstone SG, Cordy JT, Bird SR, et al. Comparison of anthropometry, upper-body strength, and lower-body power characteristics in different levels of australian football players. The Journal of Strength & Conditioning Research. 2015;29(3):826-34.
57. Woods CTE, Raynor AJ, Bruce L, McDonald Z, Collier N. Predicting playing status in junior Australian Football using physical and anthropometric parameters. Journal of Science and Medicine in Sport. 2015;18(2):225-9.
58. Gabbett TJ, Jenkins DG, Abernethy B. Relative importance of physiological, anthropometric, and skill qualities to team selection in professional rugby league. Journal of Sports Sciences. 2011;29(13):1453-61.
59. Till K, Cobley S, O'Hara J, Chapman C, Cooke C. A longitudinal evaluation of anthropometric and fitness characteristics in junior rugby league players considering playing position and selection level. Journal of Science and Medicine in Sport. 2013;16(5):438-43.
60. Enoksen E, Tønnessen E, Shalfawi S. Validity and reliability of the Newtest Powertimer 300-series® testing system. Journal of Sports Sciences. 2009;27(1):77-84.
61. Foran B. High-performance sports conditioning: Human Kinetics; 2001.
62. Garrido N, Marinho DA, Barbosa TM, Costa AM, Silva AJ, Pérez-Turpin JA, et al. Relationships between dry land strength, power variables and short sprint performance in young competitive swimmers. Journal of human sport and exercise. 2010(II).
63. McGee KJ, Burkett LN. The national football league combine: a reliable predictor of draft status? The Journal of Strength & Conditioning Research. 2003;17(1):6-11.
64. Baker D, Nance S. The relation between running speed and measures of strength and power in professional rugby league players. The Journal of Strength & Conditioning Research. 1999;13(3):230-5.
65. Barr MJ, Sheppard JM, Gabbett TJ, Newton RU. Long-term training-induced

changes in sprinting speed and sprint momentum in elite rugby union players. The Journal of Strength & Conditioning Research. 2014;28(10):2724-31.
66. Hoffman JR, Fry AC, Howard R, Maresh CM, Kraemer WJ. Strength, speed and endurance changes during the course of a division I basketball season. J Appl Sport Sci Res. 1991;5(3):144-9.
67. Young WB, Newton RU, Doyle TLA, Chapman D, Cormack S, Stewart C, et al. Physiological and anthropometric characteristics of starters and non-starters and playing positions in elite Australian Rules football: a case study. Journal of Science and Medicine in Sport. 2005;8(3):333-45.
68. Gabbett TJ. Influence of physiological characteristics on selection in a semi-professional first grade rugby league team: a case study. Journal of Sports Sciences. 2002;20(5):399-405.
69. Sheppard JM, Young WB. Agility literature review: Classifications, training and testing. Journal of Sports Sciences. 2006;24(9):919-32.
70. Scanlan A, Humphries B, Tucker PS, Dalbo V. The influence of physical and cognitive factors on reactive agility performance in men basketball players. Journal of Sports Sciences. 2014;32(4):367-74.
71. Spiteri T, Nimphius S, Hart NH, Specos C, Sheppard JM, Newton RU. Contribution of strength characteristics to change of direction and agility performance in female basketball athletes. The Journal of Strength & Conditioning Research. 2014;28(9):2415-23.
72. Stewart PF, Turner AN, Miller SC. Reliability, factorial validity, and interrelationships of five commonly used change of direction speed tests. Scandinavian Journal of Medicine & Science in Sports. 2014;24(3):500-6.
73. Léger LA, Mercier D, Gadoury C, Lambert J. The multistage 20 metre shuttle run test for aerobic fitness. Journal of Sports Sciences. 1988;6(2):93-101.
74. Flouris AD, Metsios GS, Koutedakis Y. Enhancing the efficacy of the 20 m multistage shuttle run test. British Journal of Sports Medicine. 2005;39(3):166-70.
75. Burgess D, Naughton G, Hopkins W. Draft-camp predictors of subsequent career success in the Australian Football League. Journal of Science and Medicine in Sport. 2012;15(6):561-7.
76. Currell K, Jeukendrup AE. Validity, Reliability and Sensitivity of Measures of Sporting Performance. Sports Medicine. 2008;38(4):297-316.
77. Davis JA, Brewer J, Atkin D. Pre season physiological characteristics of English first and second division soccer players. Journal of Sports Sciences. 1992;10(6):541-7.
78. Castagna C, Manzi V, Impellizzeri F, Weston M, Barbero Alvarez JC. Relationship between endurance field tests and match performance in young soccer players. The Journal of Strength & Conditioning Research. 2010;24(12):3227-33.
79. Gabbett TJ, Seibold AJ. Relationship between tests of physical qualities, team selection, and physical match performance in semiprofessional rugby league players. The Journal of Strength & Conditioning Research. 2013;27(12):3259-65.
80. Higham DG, Pyne DB, Anson JM, Eddy A. Physiological, anthropometric, and performance characteristics of rugby sevens players. International Journal of Sports Physiology and Performance. 2013;8(1):19-27.

81. Deprez D, Coutts AJ, Lenoir M, Fransen J, Pion J, Philippaerts R, et al. Reliability and validity of the Yo-Yo intermittent recovery test level 1 in young soccer players. Journal of Sports Sciences. 2014;32(10):903-10.
82. Wells KF, Dillon EK. The sit and reach—a test of back and leg flexibility. Research Quarterly American Association for Health, Physical Education and Recreation. 1952;23(1):115-8.
83. Hui SS, Yuen PY. Validity of the modified back-saver sit-and-reach test: a comparison with other protocols. Med Sci Sports Exerc. 2000;32(9):1655-9.
84. Kendall FP. Muscles: testing and function with posture and pain. 5th ed. Baltimore, MD: Lippincott Williams & Wilkins; 2005.
85. Erkula G, Demirkan F, Alper Kılıç B, Kıter E. Hamstring shortening in healthy adults. Journal of Back & Musculoskeletal Rehabilitation. 2002;16(2/3):77.
86. Jones CJ, Rikli RE, Max J, Noffal G. The reliability and validity of a chair sit-and-reach test as a measure of hamstring flexibility in older adults. Research Quarterly for Exercise and Sport. 1998;69(4):338-43.
87. Ayala F, Sainz de Baranda P, De Ste Croix M, Santonja F. Absolute reliability of five clinical tests for assessing hamstring flexibility in professional futsal players. Journal of Science and Medicine in Sport. 2012;15(2):142-7.
88. Hiller CE, Refshauge KM, Herbert RD, Kilbreath SL. Balance and recovery from a perturbation are impaired in people with functional ankle instability. Clinical Journal of Sport Medicine. 2007;17(4):269-75.
89. Pourkazemi F, Hiller C, Raymond J, Black D, Nightingale E, Refshauge K. Using balance tests to discriminate between participants with a recent index lateral ankle sprain and healthy control participants: a cross-sectional study. Journal of Athletic Training. 2016;51(3):213-22.
90. Sherar LB, Mirwald RL, Baxter-Jones ADG, Thomis M. Prediction of adult height using maturity-based cumulative height velocity curves. The Journal of Pediatrics. 2005;147(4):508-14.
91. Carter JL, Heath BH. Somatotyping: development and applications: Cambridge University Press; 1990.
92. Perroni F, Vetrano M, Camolese G, Guidetti L, Baldari C. Anthropometric and somatotype characteristics of young soccer players: Differences among categories, subcategories, and playing position. The Journal of Strength & Conditioning Research. 2015;29(8):2097-104.
93. Arellano R, Pardillo S, Gavilán A, editors. Underwater undulatory swimming: Kinematic characteristics, vortex generation and application during the start, turn and swimming strokes. Proceedings of the XXth International Symposium on Biomechanics in Sports, Universidad de Granada; 2002.
94. Georgopoulos NA, Markou KB, Theodoropoulou A, Benardot D, Leglise M, Vagenakis AG. Growth retardation in artistic compared with rhythmic elite female gymnasts. The Journal of Clinical Endocrinology & Metabolism. 2002;87(7):3169-73.
95. Malina RM, Rogol AD, Cumming SP, Coelho e Silva MJ, Figueiredo AJ. Biological maturation of youth athletes: assessment and implications. British Journal of Sports Medicine. 2015;49(13):852-9.
96. Gualdi-Russo E, Zaccagni L. Somatotype, role and performance in elite volleyball players. Journal of Sports Medicine and Physical Fitness. 2001;41(2):256.

97. Stewart A, Marfell-Jones M, International Society for Advancement of K. International standards for anthropometric assessment. Lower Hutt, New Zealand: International Society for the Advancement of Kinanthropometry; 2011.
98. Perini TA, Oliveira GLd, Ornellas JdS, Oliveira FPd. Technical error of measurement in anthropometry. Revista Brasileira de Medicina do Esporte. 2005;11(1):81-5.
99. Hodgdon JA, Beckett MB. Prediction of percent body fat for US Navy men from body circumferences and height. NAVAL HEALTH RESEARCH CENTER SAN DIEGO CA; 1984.
100. Hodgdon JA, Beckett MB. Prediction of percent body fat for US Navy women from body circumferences and height1984. 30 p.
101. Milsom J, Naughton R, O'Boyle A, Iqbal Z, Morgans R, Drust B, et al. Body composition assessment of English Premier League soccer players: a comparative DXA analysis of first team, U21 and U18 squads. Journal of Sports Sciences. 2015;33(17):1799-806.
102. Ackland TR, Lohman TG, Sundgot-Borgen J, Maughan RJ, Meyer NL, Stewart AD, et al. Current status of body composition assessment in sport. Sports Medicine. 2012;42(3):227-49.
103. Duthie G, Pyne D, Hooper S. Applied physiology and game analysis of rugby union. Sports Medicine. 2003;33(13):973-91.
104. Bahr R, Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. British Journal of Sports Medicine. 2005;39(6):324-9.
105. Dewar DL, Lubans DR, Plotnikoff RC, Morgan PJ. Development and evaluation of social cognitive measures related to adolescent dietary behaviors. International Journal of Behavioral Nutrition and Physical Activity. 2012;9(1):36.
106. Lubans DR, Lonsdale C, Plotnikoff RC, Smith J, Dally K, Morgan PJ. Development and evaluation of the motivation to limit screen-time questionnaire (MLSQ) for adolescents. Preventive Medicine. 2013;57(5):561-6.
107. Niven P, Scully M, Morley B, Crawford D, Baur LA, Wakefield M. Socioeconomic disparities in Australian adolescents' eating behaviours. Public Health Nutrition. 2014;17(12):2753-8.
108. Scott JJ, Morgan PJ, Plotnikoff RC, Lubans DR. Reliability and validity of a single-item physical activity measure for adolescents. Journal of Paediatrics and Child Health. 2015;51(8):787-93.
109. Gwynn JD, Flood VM, D'Este CA, Attia JR, Turner N, Cochrane J, et al. The reliability and validity of a short FFQ among Australian Aboriginal and Torres Strait Islander and non-Indigenous rural children. Public Health Nutrition. 2011;14(3):388-401.
110. Larsen CH, Alfermann D. Understanding dropout in the athlete development process. In: Baker J, Cobley S, Schorer J, Wattie N, editors. Routledge Handbook of Talent Development in Sport2017. p. 325-35.
111. Knight CJ. Family influences of talent development in sport. In: Baker J, Cobley S, Schorer J, Wattie N, editors. Routledge Handbook of Talent Development in Sport2017. p. 181-91.

Research into optimising performance from a multidisciplinary team: the case of the IGOID research group

Leonor Gallardo[1], Enrique Colino[1], José Luis Felipe[2,1], Jorge García-Unanue[2,1], Manuel León[1], Jorge López-Fernández[1], Javier Sánchez-Sánchez[2,1] and Esther Ubago-Guisado[1]

1. Introduction

The IGOID Group *(Grupo IGOID: Investigación en la Gestión de Organizaciones e Instalaciones Deportivas)* is a research group specialising in research in management of organisations and sports facilities. However, the world of sport has evolved with great speed and with a marked interdisciplinarity. Therefore, the analysis of performance in the different manifestations of sport has become a subject of relevant importance in the world of research in the sports sciences. This way, in the IGOID Group (www.igoid.es) we have been working for years in this sector. Our research is related with sports facilities and the quality of life that we want to give to our society. Therefore, we are going to present our research, which is divided in different areas of study: sports surfaces and their influence of performance; new technologies in the control and prevention of injuries, growth and bone development; and optimisation of management in sports companies. The rest of the chapters are divided in one part for each area of study.

2. Sports surfaces and their influence on performance

Professional football is commonly played on a natural grass surface as it is considered the most suitable surface for this sport. However, semi-professional and amateur football are increasingly opting more for artificial turf systems of third generation due to the social, environmental and economic return of these surfaces.[1,2] The fast growth in the use of artificial turf pitches in Spain, as well as the diverse use of materials for their construction, led the IGOID Group to raise two fundamental questions about these surfaces: i) how adequate are these surfaces for football practice? ii) what do the main agents involved in the game think about them?

1. Grupo IGOID. Universidad de Castilla-La Mancha
2. Universidad Europea de Madrid. Facultad Ciencias de la Actividad Física y el Deporte

Regarding the first question, the quality reached by third-generation systems of artificial turf made international organisations, like the European Committee for Standardization or the Fédération Internationale de Football Association, accept them for playing football.[1] However, as any manufactured product it requires fulfilling a minimum standard to be used for playing a sport on it. For that reason, both these entities developed standards of certification for artificial surfaces which are constantly updated and reviewed.[3]

After studying the mechanical properties of 20 artificial turf pitches across Spain, Burillo et al.[4] concluded that the mechanical properties of artificial turf systems of third generation are influenced by different parameters such as the type of fibre, type of rubber infill, elastic base, years of use and maintenance system. Therefore, when implementing a new surface of artificial turf, all these parameters must be considered. Likewise, this study also reveals that despite the existence of a standardised norm for these surfaces, they were not fulfilled by the artificial turf fields of Spain, increasing the risk of suffering an injury. These conclusions were also supported by Sánchez-Sánchez, et al.[5] after analysing four different systems of artificial turf. Despite this work only analysing four surfaces, they found that the choice of materials of support can increase the lifetime of the artificial turf system considerably. Furthermore, a bad election of these materials together with the lack of maintenance can make the surface unusable in a few years. Therefore, when implementing a new field of artificial turf, the manager must consider the structural components of the system and the maintenance that is going to be applied and the number of uses per week. Finally, to provide the best experience possible and avoid unnecessary risks, the manager should check that the new field of artificial turf has been built according to the standardised norms and that the system maintains these properties over time.

Concerning the second question, several authors have reported greater footballer satisfaction with natural surfaces compared to synthetic ones,[6,7] even though synthetic systems seem to provide similar performance to natural grass fields.[8] The work from IGOID Group reveals that the satisfaction that artificial turf is positively valued by players, coaches and referees.[1,2] However, satisfaction level is related with previous experience, as footballers who used to play on dust pitches reported higher satisfaction than those who used to do it on grass surfaces. Within this topic, Andersson et al.[6.] identified that the style of play is modified by the type of surface and by the perception of the footballers. For instance, players tend to avoid tackles and increase the number of short passes when playing on a field of artificial turf. Thus, this can explain the difference of satisfaction level according to the previous experience.

With the development of tracking technologies like Global Positioning System (GPS), it has been possible to study how the game surface influences the performance of footballers.[7-9] Thus, comparative studies between artificial and turf pitches indicate similar players' responses (physical and physiological) regardless of the surface used.[7,8,10] However, these studies only focused on standardised tests, so tactical and technical actions were not studied. The main conclusion of these studies is that the new third-generation pitches do not cause greater fatigue, do not delay recovery or reduce sprint performance. On the other hand, longitudinal studies about injury rates on artificial turf and natural grass prove that playing football on the first surface is not riskier than on natural grass.[11] Nonetheless, these authors did not analyse the mechanical properties of the fields used in their studies, so they could not relate these results with the mechanical properties of the newest fields of artificial turf.

To increase the understanding about the role of mechanical properties on players' responses when playing on both surfaces, the IGOID Group has developed two studies (not published by August 2017). Both studies used the same two surfaces whose mechanical properties were analysed (Table 1)

	Artificial	Natural	*p* value
FR (%)	43.59±5.09*	49.69±6.33	$p = 0.07$
StV (mm)	6.77±0.60	5.29±0.83	$p < 0.01$
ER (%)	53.84±2.23	39.22±6.76	$p < 0.01$

Note: * Non-compliance with the specifications of the standard EN 15330-1:2014. FR = force reduction; StV = standard vertical deformation; ER = energy restitution

Table 1. Mechanical Properties of Both Selected Surfaces

The first work analyses the accumulated fatigue of sixteen players after performing the first three bouts of a soccer simulation protocol (three blocks of 16 min with 3 min recovery between blocks,[10]). The results showed similar muscle response on both surfaces right after finishing the test, as players got similar performance in a countermovement jump. Likewise, through a tensiomyography it was analyse the response of both biceps femoris and rectus femoris to an electric stimulus not finding differences according to the surface. Therefore, despite the existing differences of mechanical properties of both surfaces, they were not high enough to cause different impact on muscle fatigue.

The second work also used the first three bouts of a soccer simulation protocol, but in this case, we analysed the physiological responses and performance of players on the test. Each bout of the soccer simulation protocol is composed of eight cycles and one repeated sprint (RS: 6 × 15 m sprints departing every 18 s) block between the fourth and fifth cycles structured as follows: i) 3 × 20 m at a walking pace of 1.43 m/s; ii) 1 × sprint-agility run (S-AR) at maximal intensity (20 s for sprint and recovery); iii) 3 × 20 m at a running speed of 2.5 m/s; iv) 3 × 20 m at a running speed of 4.0 m/s. After analysing the performance of players on each sprint-agility run and the repeated sprint of the three bouts, players presented lower time sprint in some part of agility test on artificial turf. Therefore, the higher energy restitution of the artificial turf seems to cause faster performance in non-linear sprints. Nevertheless, these findings suggest that players should not present lower performance in linear and non-linear sprints when playing football on artificial turf than on natural grass.

While these results strengthen the previous findings,[7,8,10] care must be taken when evaluating them, because as mentioned previously, the mechanical properties of an artificial turf pitch can differ greatly between systems.[1,5,12,13] In fact, through different investigations,[14-17] the IGOID Group has proved a significant variation in footballers' response in function of the type of artificial turf used in both real-life football situations and in standardised match tests. Therefore, a greater physiological value of peak heart rate has been found on artificial turf systems with greater damping capacity, while harder surfaces are related with higher dependence of creatine phosphate.[9,17] Furthermore, the main differences found between artificial systems is in actions like change of direction and turns, where factors like rotational traction and energy restitution of the ground seem to have a great influence.[5,17]

Conclusions

In conclusion, the structural components of the system together with other factors such as number of hours of use per week or maintenance plan as they play a key role on the mechanical properties of artificial turf systems. Moreover, even though natural grass is still perceived as the most suitable surface for playing football, the findings of previous studies suggest that artificial turf systems can provide similar performance to natural grass fields, not increasing the risk of suffering an injury. However, it is required that artificial turf systems fulfil the international standards as those that do not meet them could negatively affect players' performance or security.

3. New technologies in the control and prevention of injuries

Our research is related with sports facilities and the quality of life that we want to give to our society. Therefore, we can focus on topics of research rather than in the equipment. These materials can be then mentioned as recent technology that supports the advanced research made by the group (e.g. GPS technology, tracking technology and positioning of sports facilities, thermography, tensiomyography to different studies on surfaces and bone mass, etc.). Thereby, the main research topic is the importance of guaranteeing the correct use of artificial turf, with all its qualities in performance and its optimisation by sports companies.

Global Positioning System (GPS)

GPS devices register the activity and physiological profiles of players with a sampling frequency of 10 Hz. The devices are located at the top part of the player's back, inside a specific chest guard provided by the manufacturer. Similarly, heart rate bands are located at chest level through elastic bands. Afterwards, the data are downloaded to a personal computer and analysed using software provided by the manufacturer. The variables obtained by these devices provide information on physical and physiological performance of athletes.

Movement patterns — external load

The GPS devices attached to the players provided information about the total distance covered during the game (DT), the maximum speed

(V_{max}) and average speed (V_{mean}) reached during matches and/or training sessions, as well as the distance covered in each one of the six locomotor categories with speed ranges adapted from previous studies:[16,17] standing (0–2 km/h), walking (2–7 km/h), easy running (7–13 km/h), fast running (13–18 km/h), high-speed running (18–21 km/h) and sprinting (>21 km/h). The actions above 13 km/h (fast running, high-speed running and sprinting) are defined as high-intensity running. The GPS software also provided information about the number, average distance and maximum average speed of the sprints (Figure 1). These actions of high intensity have been identified as the most determinant in the performance of team sports.

In the same way, the GPS devices register the maximum acceleration peaks, as well as the number of accelerations of the players in different ranges of intensity: 1.5–2 m/s^2; 2–2.5 m/s^2; 2.5–2.75 m/s^2; >2.75 m/s^2. The data of maximum peak and number of impacts during the game are obtained using the triaxial accelerometer of 100 Hz incorporated to each one of the GPS devices and classified into six categories based on the G forces reached (1 G = 9.81 m/s^2): light impact (5–6 G), light/moderate impact (6–6.5 G), moderate/heavy impact (6.5–7 G), heavy impact (7–8 G), very heavy impact (8–10 G), and severe impact (>10 G). The control of the number of accelerations and impacts on the athlete can allow the development of specific training tasks adapted to real situations of competition, reducing athlete injury risk. Like the previous variable, the load of the player can be obtained from the combination of the accelerations detected in the three planes of body motion (vertical, horizontal and anteroposterior), using the software of the GPS. The load data are presented in arbitrary units. The GPS detection of an imbalance of more than 5% can alert to a decompensation in the motor behaviour of the athlete derived from a potentially dangerous situation for the athlete's health. Finally, GPS software includes the ratio work:rest, which results from the quotient between the distance covered at speeds above 4 km/h (work phase) and the distance covered by the player at speeds below 4 km/h (rest phase).

Heart rate parameters — internal load

Internal load is an essential parameter for training control. For this, it is necessary to know the individual maximum heart rate (HR_{max}) of each athlete. Numerous specific tests are used in each sport to estimate this variable. For example, in football, the HR_{max} value can be obtained in the intermittent recovery yo-yo test to establish different categories of intensity during a match or training session: <70% HR_{max}, 70–80% HR_{max}, 80–90% HR_{max}, 90–95% HR_{max} and >95% HR_{max}. The GPS software synchronises with the HR bands and registers the time used by players in each one of the zones described above. The data are presented as relative percentages in relation to the total time played. However, the peak and average values of heart rate reached during the game and 15 min intervals are obtained in absolute (bpm) and relative (% HR_{max}) terms.

The monitoring of these variables will reveal the level of fatigue of the athlete, undertaking interventionist protocols to prevent injuries during practice (Figure 1). In this sense, the heterogeneity between the acute and chronic load experienced by the athlete has been identified as the main predictor of athlete injury incidence.[18] The use of these devices will allow the control of load, assuring homogeneity between these parameters and reducing injury risk in athletes.

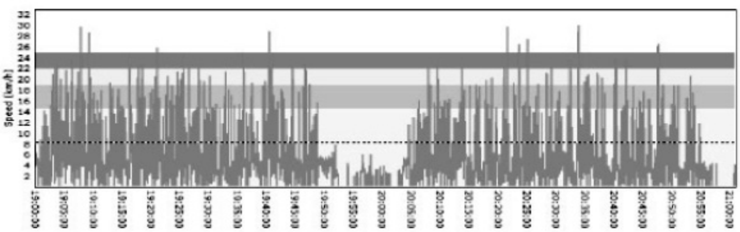


Figure 1. Profile of a footballer's activity during a real game situation

Tensiomyography (TMG)

Tensiomyography is a non-invasive evaluation technique that allows the evaluation of contractile capacities of an athlete's muscles. This control tool allows the identification of muscle imbalances in athletes and the discovery of neuromuscular fatigue after an effort.[19] This device measures: maximal displacement (Dm) given by the radial movement of muscle belly expressed in mm and depends on the muscle tone or stiffness; contraction time (Tc), the time between 10 and 90% of Dm; sustain time (Ts), the time in which the muscle response remains >50% of Dm; delay time (Td), also known as reaction or activation time, is the time between the initiation and 10% of Dm; and half-relaxation time (Tr), the time in which the muscle response decreases from 90 to 50% of Dm muscle (Figure 2).

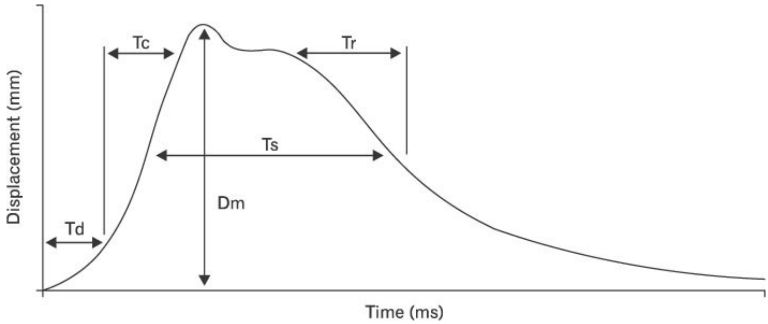


Figure 2. Tensiomyography (TMG) parameters definition.[19] Dm=maximal displacement; Tc=contraction time, Ts=sustain time, Td=delay time and Tr=half-relaxation time.

A small electric stimulation is produced on the required muscle. This stimulus is measured by placing a digital transducer perpendicular to the muscle belly. The stimulation of the selected muscle is made using two self-adhesive electrodes placed equidistant to the point where the measurement will be made. The proximal electrode corresponds to the anode and the distal to the cathode. The stimulus is produced by a system electro-stimulator of 1 ms duration. The amplitude range of the electrical stimulus can be from 0 to 110 mA. The measurement protocol varies according to the muscle group evaluated. The comparison of variables in the same athlete will allow detecting neuromuscular asymmetries, establishing the level of muscle recovery after a training stimulus and discovering the fatigue accumulated in the muscle groups evaluated.[20] This information will guarantee an exhaustive control of the physical load of the athlete and the risk of muscle injury during practice. Finally, a periodic evaluation of these variables will clarify when an athlete can return to competition after an injury.

Thermography

Thermography has become a powerful research instrument in many applications at mechanical, electrical, military, construction and medical levels. Due to its non-invasive character, infrared thermography (IRT) can be defined as data analysis by using non-contact thermal imaging instruments. Thermographic cameras detect radiation within the electromagnetic spectrum range and produce images of this radiation called thermograms. This method provides real-time images at a distance, with measurements of the surface temperature, in this case, skin temperature. It is a highly sensitive diagnostic method, fast, totally safe, harmless, highly reproducible and does not involve radiation emission.[21] This technique allows the visualisation of the surface temperature with sensitivity above 0.025°C and an accuracy of 1%, non-invasively and without physical contact with the subject.[21] These characteristics allow scientists to obtain a general thermal profile of the subject and if carried out routinely, lead to a real-time monitoring of skin temperature, which allows obtaining information on the complex thermoregulation system of the human body.

Currently, there are some articles[21,22] in the literature that indicate the possibility of using thermography for: evaluating muscle recovery; programming training sessions; modifying workouts; estimating maximum oxygen consumption VO2max; identifying edemas, varicose veins or ischemia; and identifying muscle injuries. Since injuries trigger inflammatory processes and inflammation causes heat by increasing basal metabolism, the level of inflammation can be assessed using temperature gradients. Since thermography allows for the detection of small temperature variations, thermographic images show, prematurely, the start of inflammatory processes that still have not shown symptoms (pain, edema or paraesthesia), acting as a preventive tool.

Thermal symmetry of the human body has been defined as the 'degree of similarity' of two regions of interest (ROI) reflected along the main longitudinal axis of the human body, which are equal in form and size and were taken at the same angle.[23] Pathological conditions, like musculoskeletal disorders and traumatic injuries, affect the thermal distribution of the surface temperature, producing changes in its natural symmetrical pattern. Thermal symmetry values have been considered important for the evaluation of athletes after an injury.[24] Thermal asymmetries do not usually exceed values over 0.25°C. Different studies have shown that greater asymmetries (above 0.60°C) may correspond to musculoskeletal injuries (Figure 3). For this reason, infrared thermography has been consolidated as a valuable tool for clinically evaluating the progress and treatment of sports injuries and musculoskeletal disorders.

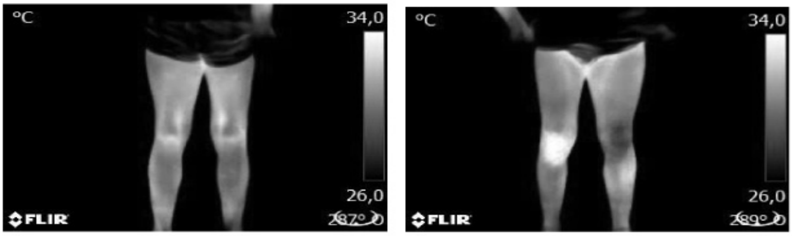


Figure 3. Thermal asymmetry detected in a knee injury in a futsal player (IGOID archive)

Conclusions

In conclusion, the use of new technologies applied to sport allows a detailed control of accumulated load of an athlete during the season. Maybe the most important one is the GPS technology about the tactical and performance applications. The interpretation of this information facilitates the improvement of physical planning carried out by teams and/or athletes, as well as for early injury diagnosis. Therefore, their incorporation in sport nowadays has become indispensable. The multifactorial character of these protocols, together with additional technology associated with heart rate variability, balance and plantar pressure among others, as well as controlling contextual variables like the playing surface,[17,25] increases the validity and reliability of interventional methodologies used by this research group in relation with football performance and injury prevention.

4. Growth and bone development

In the last few years, there has been an alarming increase in overweight individuals and obesity, especially among young people, due to, among other factors, low levels of physical activity. Obesity in childhood is closely related to adult obesity, because these children have twice the risk of developing obesity in later life than those who are not obese.[26] Studies such as Boreham et al.[27] show that physical activity during childhood prevents obesity in later life. For these reasons, the prevention of obesity in childhood is an international priority given the impact it has on chronic diseases, general health, development, and well-being. It is known that physical exercise and sport in general regulate fat and muscle mass of children. On the other hand, the type of sport practised influences the body composition development.[28] Each sport due to its characteristics and requirements is associated with different player profiles. Within this framework, the IGOID Group developed an experimental study to analyse the differences in fat mass and lean mass of girls playing different sports, and which the main conclusion was: 'Girls who practise regular high-impact sports (football, basketball and handball) and low-impact (swimming) have lower fat mass and higher lean mass compared to the inactive controls at prepubescent and puberty.

Likewise, the interest in bone health in childhood has grown meaningfully because of the increase of osteoporosis cases in adults. Up to 60% of osteoporosis cases in adult life are related with acquired bone mineral content during adolescence.[29] Osteoporosis is considered a public health problem due to the high number of people who suffer from it and its economic repercussions that are generated during treatment and rehabilitation.[30] An increment in the level of physical activity in children would result in higher bone mass accrual and a decrease in the risk of suffering bone fractures during adulthood.[31] Research carried out by Vicente-Rodriguez et al.[32] showed that boys engaged in a high-impact sport like football increased bone mass values compared to inactive boys. Nevertheless, while practising low-impact sports, as for example swimming[33] and cycling[34], the bones do not get so many stimuli, so the bone density values are lower.

Therefore, due to lack of research with girls, we carried out a second study[35] with the objective of comparing the differences in bone mass in girls according to the type of sport practised. The main conclusion we obtained from this research was: 'Girls who practise high-impact sports (football, basketball and handball) have higher bone mass compared to girls who practise low-impact sports (swimming) and controls at puberty.' On the other hand, muscle mass is known as an important factor for predicting bone mass increment during puberty.[36] Although the role of muscle mass in the development of bone mass is evident, the association between fat mass and bone mass generates certain debate. Some studies in girls show that fat mass is positively related with bone mass.[37-39] However, other studies support the idea that bone mass is negatively related with bone mineral density in boys.[40]

In this sense, through a third and fourth study using a dual-energy X-ray absorptiometry scan (DXA),[41,42] we analysed the influence of fat mass, lean mass, maximum oxygen consumption, weekly training hours and years of sports practice on bone mass in girls; and we examined the association between muscular and cardiorespiratory fitness with bone mineral density and hip geometry in boys. The main conclusions obtained were: '1) During puberty, bone mass in girls is related to lean mass, cardiorespiratory fitness and weekly hours of sports practice; 2) Vigorous physical activity does not seem to explain the association between fitness (cardiorespiratory and muscular) and bone parameters (bone mineral density and hip geometry), while lean mass plays a key role in this association in young males.'

Finally, we must also take extrinsic factors into account like the playing surface. The affinity between the player and the playing surface is important for player's performance and health. Most researches have focused on studying the influence on injury rate[43] and performance[17]. Up to date, only one transversal study in children has been done by Plaza-Carmona et al.[44] that has addressed the issue on outdoor surfaces. In that study, no significant differences were found in bone mass in the limb, pelvis and hip regions between practising football on dust pitches and artificial turf. Thus, in a fifth study[41] we compared the differences in bone mass in girls playing on different surfaces, obtaining as a main conclusion: A hard playing surface, with less vertical deformation and force reduction and with higher energy return, is associated with higher levels of bone mass in girls, regardless of the sport they practise.

Conclusions

The conclusions of our studies are that regular practice of both high-impact and low-impact sports is associated with a lower fat mass and higher lean mass in girls during puberty. In addition, girls who practise high-impact sports (football, basketball and handball) have higher bone mass compared to those who practise low-impact sports (swimming). During puberty, bone mass is related to lean mass, cardiorespiratory fitness and weekly hours of sports practice. Also, vigorous physical activity does not seem to explain the association between fitness (cardiorespiratory and muscular) and bone parameters (bone mineral density and hip geometry), while lean mass plays a key role in this association in young males. Finally, a hard-playing surface, with less vertical deformation and force reduction and with higher energy return, is associated with higher levels of bone mass in girls, regardless of the sport they practise. Future research is needed to know the influence of the playing surfaces on sports injuries, to find a balance between bone development and injury prevention.

5. Optimisation of management in sports companies

Performance optimisation in sport is usually seen as improvement in physical and sports performance. However, there is another field that has been studied on performance improvement: sports management, in this case, through the optimisation of business performance in sports organisations. We understand that this field of study is vital for sports development, as growth and quality improvement in sports organisations will help improve resources and installations available for athletes, as well as reducing barriers for sports practice. Following the evolution of research by the IGOID Group in these sections, we can find three work areas in which the group has collaborated: i) management models and systems; ii) finance of local sports management; iii) fitness sector management. We will divide this section into these areas.

Management models and systems

In this area we can find the first article of international relevance published by this group.[45] This paper analyses manager requirements for sports facilities to obtain comprehensive sports management through a qualitative research by a group of experts. In this paper, needs were anticipated that are currently a reality, like management using mobile devices or different billing elements, timetables and clients that are now incorporated into popular CMS software (i.e. customer relationship management software, a kind of software usually used by sports centres and marketed by several companies).

After which, the IGOID Group started to work on big data concepts applied to sport, in this case, from a management point of view. Taking advantage of the data published in the Spanish sports facilities census, two studies were published. In the first research[46] a performance measurement system in terms of sports facility availability is presented, obtaining a synthetic indicator that allows cataloguing Spanish regions based on the development of their sports infrastructure. After a factorial analysis, a total indicator is created, as well as three partials ones based on density, quantity and quality of sports facilities. In the second research[47] an analysis of the influence of the socioeconomic environment on the sports infrastructure development was carried out, finding clear relationships. Thus, the level of physical activity practice and the economic level of the population are significantly related with the development of sports infrastructure (Table 2).

	GDP per capita	Unemployment rate	Market share per capita	Tourism index per capita	Index of economic activity per capita	Physical activity index
Sports infrastructure development	0.541*	-0.142	0.400	0.585*	0.385	0.561*

Note: * = p<0.005

Table 2. Pearson's correlation between sports infrastructure development and socioeconomic factors (adapted from[47])

Finance of local sports management

Public administration has undergone many changes in its interests since the implementation of New Public Management. Since then, interest in performance assessment and measurement has increased.[48] Within the most affected different local public services, we can find municipal sports services given their growth over the years.[47] Generally, local public sports services, in most of the European and South American countries, work to provide access to sports facilities and activities for all sectors of the population and to achieve the highest levels of physical activity among their population.[49] To do this, they manage sports activities, as well as their own sports facilities.[50,51]

Therefore, a series of studies have been developed to show the reality regarding the performance of municipal sports services, with a view of improving their management and marking data that allows to set achievable and realistic performances targets. In this sense, the researches[52,53] are highlighted. In these studies, the IGOID Group shows national reference values and a benchmark of financial condition (i.e. system for analysing the economic performance of municipal services,[54]) in municipal sports agencies from 2002 to 2011 (Table 3). Thanks to these results, it was demonstrated that management performance results that theoretically were correct (and up to now were taken as reference points) underestimate or overestimate the results that could be considered as good or bad depending on the reality of the sector. After this, the study is extended by García-Unanue et al.[55], who analysed how the environment can affect these indicators, in a way that the importance of each decision on the performance results can be considered and which part can be attributed to uncontrollable environmental factors. The study shows that in the case of municipal sports services the political orientation does not have a clear effect, while the population is determinant, making the service management in big populations more difficult.

	Net Saving Index per capita							
	p25	p50	p75	%	mean	sd	CV	ANOVA
2002	-0.369	0.539	2.178	66.667	1.219	5.126	n.a.	
2003	-0.426	0.797	1.961	68.041	0.855	5.914	n.a.	
2004	-0.536	0.694	2.323	64.840	1.111	5.079	n.a.	
2005	-0.032	0.699	2.360	73.934	1.767	6.467	n.a.	
2006	-0.135	0.799	2.375	70.142	1.086	6.989	n.a.	
2007	-0.481	0.700	2.793	67.111	2.221	7.660	n.a.	$F = 1.346$ $p = 0.208$
2008	-0.851	0.546	2.608	64.186	0.872	5.063	n.a.	
2009	-0.383	0.616	3.053	69.484	1.207	6.480	n.a.	
2010	-0.713	0.585	3.083	64.384	1.424	6.038	n.a.	
2011	-1.070	0.385	2.144	63.333	0.520	6.118	n.a.	
WP	-0.450	0.636	2.388	67.181	1.237	6.155	n.a.	
	Non-Financial Budgetary Result Index							
	p25	p50	p75	%	mean	sd	CV	ANOVA
2002	1.039	0.993	0.964	57.658	1.016	0.140	0.137	
2003	1.034	0.997	0.958	55.155	1.004	0.120	0.120	
2004	1.034	0.998	0.955	56.164	1.008	0.126	0.125	
2005	1.018	0.991	0.942	63.981	0.993	0.150	0.151	
2006	1.022	0.991	0.946	62.085	0.987	0.104	0.105	
2007	1.024	0.993	0.947	61.778	0.984	0.123	0.125	$F = 2.398$ $p = 0.010$
2008	1.045	0.998	0.950	53.953	1.008	0.133	0.132	
2009	1.032	0.998	0.955	55.399	1.015	0.173	0.171	
2010	1.034	0.999	0.959	52.511	1.000	0.126	0.126	
2011	1.056	1.000	0.970	52.857	1.032	0.171	0.165	
WP	1.032	0.996	0.955	57.176	1.005	0.139	0.138	

Note: % = Percentage of institutions with adequate theoretical results; WP = Whole Period.
Table 3. Descriptive statistics, benchmarks and ANOVA results[53]

Self-Financing							
p25	p50	p75	%	mean	sd	CV	ANOVA
0.182	0.306	0.460	21.622	0.355	0.272	0.767	
0.176	0.278	0.462	22.165	0.352	0.283	0.803	
0.173	0.295	0.477	21.005	0.353	0.274	0.778	
0.169	0.284	0.441	19.431	0.325	0.233	0.717	
0.173	0.285	0.455	19.905	0.325	0.228	0.702	
0.175	0.264	0.432	17.333	0.316	0.222	0.702	$F = 1.204$ $p = 0.288$
0.187	0.265	0.412	17.674	0.317	0.211	0.666	
0.183	0.283	0.448	20.657	0.326	0.212	0.650	
0.188	0.303	0.484	23.288	0.362	0.298	0.822	
0.193	0.304	0.486	24.286	0.358	0.239	0.667	
0.178	0.287	0.453	20.711	0.339	0.249	0.735	

Current Expenditures per capita							
p25	p50	p75	%	mean	sd	CV	ANOVA
19.586	30.775	43.896	n.a.	36.890	28.074	0.761	
19.909	31.508	44.290	n.a.	36.067	24.111	0.669	
21.285	34.266	51.476	n.a.	41.031	34.859	0.850	
21.270	34.705	50.609	n.a.	41.474	33.336	0.804	
23.393	36.848	54.987	n.a.	44.392	38.325	0.863	
25.253	40.312	61.266	n.a.	47.299	37.213	0.787	$F = 4.130$ $p < 0.001$
25.212	41.498	63.919	n.a.	49.620	38.797	0.782	
27.277	41.991	63.150	n.a.	50.413	40.126	0.796	
25.357	39.528	58.654	n.a.	48.386	44.188	0.913	
23.440	38.555	57.126	n.a.	47.147	44.656	0.947	
23.010	36.905	55.800	n.a.	44.337	37.208	0.839	

Fitness sector management

After analysing the performance of the public sports sector, the following question arises: What happens with the financial performance of the private sector? First, it is necessary to point out that the private sports sector orientated towards sport for-all is mainly developed for the fitness sector. The fitness sector has grown enormously in recent years, with strong chains and companies that each year have created aggressive expansion plans.[56] However, over the last years, performance problems have begun, with annual client turnover rates of between 60.5 and 70%[57] and a decline in profits.[58] Therefore, the IGOID Group analysed the financial performance of the fitness sector over recent years, trying to detect the focus of the problem to improve performance of this sector, and in this way, improve access and quality of sports practice. Thus, Rodríguez-Cañamero et al.[59] detected lower net income over the last years, varying by size of company, in a way that the sports centres managed by microenterprises or small companies mostly exhibited these lower profits. As we can see in Figure 4, the most notable changes in the incomes and profits are in 2008, the year of the beginning of the economic crisis, and in 2012, when the VAT (value added tax) was increased. However, there is no clear trend in medium and large companies. Therefore, public strategies and policies should focus on microenterprises and small companies to facilitate the sustainability and survival of this sector.

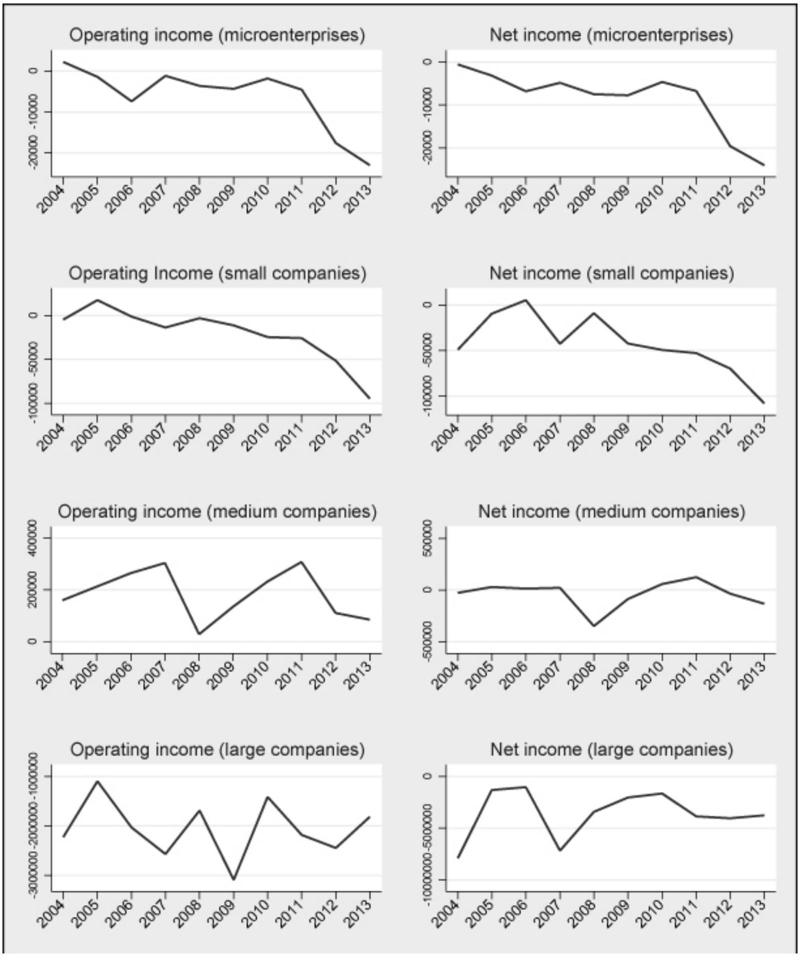


Figure 4. Evolution of fitness company results.[59] The graphs are prepared at different scales

Conclusions

This part has shown another vision of performance in sport, focusing on sports management. Good management of sports companies, public entities or clubs is vital for the health of sports systems. It is good management that breaks down practice barriers and endows the necessary resources for sports development at all levels. For this reason, the IGOID Group has materialised the research on performance of sports organisation, as if they were athletes with the aim of improving their results. Furthermore, the researches cover real problems in the different sectors of sports management such as sports facilities management, municipal sports agencies or the fitness sector, providing lines of intervention and improvement.

References

1. Burillo P, Gallardo L, Felipe JL, Gallardo AM. Artificial turf surfaces: Perception of safety, sporting feature, satisfaction and preference of football users.
Eur J Sport Sci. 2014;14(sup1):437-47.
2. Felipe JL, Gallardo L, Burillo P, Gallardo A, Sánchez-Sánchez J, Plaza-Carmona M. A qualitative vision of artificial turf football fields: elite players and coaches. S Afr J Res Sport Ph. 2013;35(2):105-20.
3. FIFA. FIFA Quality Programme for Football Turf. Handbook of Test Methods. Zurich: FIFA; 2015.
4. Burillo P, Gallardo L, Felipe, JL, Gallardo AM. Mechanical assessment of artificial turf football pitches: The consequences of no quality certification. Sci Res Essays. 2012;7(28):2457-65.
5. Sánchez-Sánchez J, Felipe JL, Burillo P, del Corral J, Gallardo L. Effect of the structural components of support on the loss of mechanical properties of football fields of artificial turf. Proc IMechE, Part P: J Sports Engineering and Technology. 2014;228(3):155-64.
6. Andersson H, Ekblom B, Krustrup P. (2008). Elite football on artificial turf versus natural grass: Movement patterns, technical standards, and player impressions. J Sports Sci. 2008;26(2):113-22
7. Nédélec M, McCall A, Carling C, Le Gall F, Berthoin S, Dupont G. (2013). Physical performance and subjective ratings after a soccer-specific exercise simulation: Comparison of natural grass versus artificial turf. J Sports Sci. 2013;31(5):529-36.
8. Hughes MG, Birdsey L, Meyers R, Newcombe D, Oliver JL, Smith PM, et al. Effects of playing surface on physiological responses and performance variables in a controlled football simulation. J Sports Sci. 2013;31(8):878-86.
9. Brito J, Krustrup P, Rebelo A. The influence of the playing surface on the exercise intensity of small-sided recreational soccer games. Hum Mov Sci. 2012;31(4):946-56.
10. Stone KJ, Hughes MG, Stembridge MR, Meyers RW, Newcombe DJ, Oliver JL. The influence of playing surface on physiological and performance responses during and after soccer simulation. Eur J Sport Sci. 2014;16(1):42-9.
11. Meyers MC. Incidence, Mechanisms, and Severity of Match-Related Collegiate Men's Soccer Injuries on FieldTurf and Natural Grass Surfaces A 6-Year Prospective Study. Am J Sports Med. 2016;doi:10.1177/0363546516671715.
12. Fleming P. Artificial turf systems for sport surfaces: current knowledge and research needs. Proc IMechE, Part P: J Sports Engineering and Technology. 2011;225(2):43-63.
13. Zanetti EM, Bignardi C, Franceschini G, Audenino AL. Amateur football pitches: mechanical properties of the natural ground and of different artificial turf infills and their biomechanical implications. J Sports Sci. 2013;31(7):767-78.
14. López-Fernández J, Gallardo L, Fernández-Luna Á, Villacañas V, García-

Unanue J, Sánchez-Sánchez J. Pitch size and Game Surface in Different Small-Sided Games. Global Indicators, Activity Profile and Acceleration of Female Soccer Players. J Strength Cond Res. 2017;doi: 10.1519/JSC.0000000000002090

15. López-Fernández J, Sánchez-Sánchez J, Gallardo L, García-Unanue J. Metabolic Power of Female Footballers in Various Small-Sided Games with Different Pitch Surfaces and Sizes. Sports. 2017;5(2):1-24.
16. Sánchez-Sánchez J, García-Unanue J, Felipe JL, Jiménez-Reyes P, Viejo-Romero D, Gómez-López M, et al. Physical and physiological responses of amateur football players on 3rd generation artificial turf systems during simulated game situations. J Strength Cond Res. 2016; doi: 10.1519/JSC.0000000000001415
17. Sánchez-Sánchez J, García-Unanue J, Jiménez-Reyes P, Gallardo A, Burillo P, Felipe JL, et al. Influence of the mechanical properties of third-generation artificial turf systems on soccer players' physiological and physical performance and their perceptions. PLoS One. 2014;9(10):e111368.
18. Jones CM., Griffiths PC, Mellalieu SD. Training load and fatigue marker associations with injury and illness: a systematic review of longitudinal studies. Sports Med. 2017;47(5):943-74.
19. Carrasco L, Sañudo B, de Hoyo M, Ochiana G. Tensiomyographic characteristics of Rectus Femoris after a single bout of intense exercise. Journal of Social Sciences. 2011;7(3):354-57.
20. Ubago-Guisado E, Rodríguez-Cañamero S, López-Fernández J, Colino E, Sánchez-Sánchez J, Gallardo L. (2017). Muscle contractile properties on different sport surfaces using tensiomyography. Journal of Human Sport and Exercise. 2017;12(1):167-79.
21. Costello J, Stewart IB, Donnelly AE, Selfe J, Karki AI. Use of thermal imaging in sports medicine research: a short report: short article. International Sportmed J. 2013;14(2):94-8.
22. Hildebrandt C, Raschner C, Ammer K. An overview of recent application of medical infrared thermography in sports medicine in Austria. Sensors. 2010;10(5):4700-15.
23. Vardasca R, Ring EFJ, Plassmann P, Jones CD. Thermal symmetry of the upper and lower extremities in healthy subjects. Thermology international. 2012;22(2):53-60.
24. Etehadtavakol M, Ng EY. Potential of Thermography in Pain Diagnosing and Treatment Monitoring. In Application of Infrared to Biomedical Sciences. Springer Singapore: Singapore; 2017. p. 19-32.
25. Felipe JL, Burillo P, Fernández Luna Á, García Unanue J. ¿Es viable el fútbol de élite sobre césped artificial? El caso FIFA Women World Cup™. Revista de Psicología del Deporte. 2016;25(3):81-4.
26. Serdula MK, Ivery D, Coates RJ, Freedman DS, Williamson DF, Byers T. Do obese children become obese adults? A review of the literature. Prev Med. 1993;22(2):167-77.
27. Boreham C, Twisk J, Neville C, Savage M, Murray L, Gallagher A. Associations between physical fitness and activity patterns during adolescence and cardiovascular risk factors in young adulthood: the Northern Ireland Young Hearts Project. Int J Sports Med. 2002;23(1):22-6.

28. Bayios IA, Bergeles NK, Apostolidis NG, Noutsos KS, Koskolou MD. Anthropometric, body composition and somatotype differences of Greek elite female basketball, volleyball and handball players. J Sports Med Phys Fitness. 2006;46(2):271-80.
29. Baroncelli GI, Bertelloni S, Sodini F, Saggese G. Osteoporosis in children and adolescents. Paediatr Drugs. 2005;7(5),295-323.
30. Cruz JG, Martínez RF, Martínez JG, Gutiérrez ES, Serrano ME, De las Deses CDH. Osteoporosis. Conceptos básicos para la práctica diaria. Revista de Especialidades Médico Quirúrgicas. 2009;14(3):128-40.
31. Karlsson MK, Nordqvist A, Karlsson C. Physical activity increases bone mass during growth. Food Nutr Res. 2008;52(1):1-10.
32. Vicente-Rodriguez G, Jimenez-Ramirez J, Ara I, Serrano-Sanchez JA, Dorado C, Calbet JA. Enhanced bone mass and physical fitness in prepubescent footballers. Bone. 2003;33(5):853-9.
33. Gómez-Bruton A, González-Agüero A, Gómez-Cabello A, Matute-Llorente A, Casajús JA, Vicente-Rodríguez G. The effects of swimming training on bone tissue in adolescence. Scand J Med Sci Sports. 2015;31(8):878-86.
34. Vlachopoulos D, Barker AR, Williams CA, Arngrimsson SA, Knapp KM., Metcalf BS, et al. The impact of sport participation on bone mass and geometry in adolescent males. Med Sci Sports Exerc. 2016;49(2):317-26.
35. Ubago-Guisado E, Gómez-Cabello A, Sánchez-Sánchez J, García-Unanue J, Gallardo L. Influence of different sports on bone mass in growing girls. J Sports Sci. 2015;33(16):1710-8.
36. Gracia-Marco L, Ortega FB, Jiménez-Pavón D, Rodríguez G, Castillo MJ, Vicente-Rodríguez G, Moreno LA. Adiposity and bone health in Spanish adolescents. The HELENA study. Osteoporos Int. 2012;23(3):937-47.
37. El Hage R, Jacob C, Moussa E, Groussard C, Pineau JC, Benhamou CL, et al. Influence of the weight status on bone mineral content and bone mineral density in a group of Lebanese adolescent girls. Joint Bone Spine. 2009;76(6):680-68
38. Pietrobelli A, Faith MS, Wang J, Brambilla P, Chiumello G, Heymsfield SB. Association of lean tissue and fat mass with bone mineral content in children and adolescents. Obes Res. 2002;10(1):56-60.
39. Sayers A, Tobias JH. Fat mass exerts a greater effect on cortical bone mass in girls than boys. J Clin Endocrinol Metab. 2010;95(2);699-706.
40. El Hage R, Moussa E, El Hage Z, Theunynck D, Jacob C. Influence of age and morphological characteristics on whole body, lumbar spine, femoral neck and 1/3 radius bone mineral apparent density in a group of Lebanese adolescent boys. J Bone Miner Metab. 2011;29(4):477-83.
41. Ubago-Guisado E, García-Unanue J, López-Fernández J, Sánchez-Sánchez J, & Gallardo L. Association of different types of playing surfaces with bone mass in growing girls. J Sports Sci. 2017;35(15);1484-92.
42. Ubago-Guisado E, Martinez-Rodriguez A, Gallardo L, Sánchez-Sánchez J. Bone mass in girls according to their BMI, VO2 max, hours and years of practice. Eur J Sport Sci. 2016;16(8):1176-86.
43. Iacovelli JN, Jingzhen Y, Thomas G, Hongqian W, Schiltz T, Foster DT. The effect of field condition and shoe type on lower extremity injuries in American Football. Br J Sports Med. 2013;47(12):789-93.

44. Plaza-Carmona M, Vicente-Rodriguez G, Martín-García M, Burillo P, Felipe JL, Mata E, et al. Influence of hard vs. soft ground surfaces on bone accretion in prepubertal footballers. Int J Sports Med. 2014;35(1):55-61.
45. Gallardo L, García-Tascón M, Burillo P. New sports management software: A needs analysis by a panel of Spanish experts. Int J Inf Manage. 2008;28(4):235-45.
46. Gallardo L, Burillo P, García-Tascón M, Salinero JJ. The ranking of the regions with regard to their sports facilities to improve their planning in sport: the case of Spain. Soc Indic Res. 2009;94(2):297-317.
47. Burillo P, Barajas Á, Gallardo L, García-Tascón M. The influence of economic factors in urban sports facility planning: a study on Spanish Regions. Eur Plan Stud. 2011;19(10):1755-73.
48. Navarro-Galera A, Ortiz-Rodríguez D, López-Hernández AM. Identifying barriers to the application of standardized performance indicators in Local Government. Public Manag Rev. 2008;10(2):241-62.
49. Gallardo L, García-Tascón M, Burillo P, Salinero JJ. Differences of needs and problematics between managers in public and private esports organisations in Spain. 2009; Paper presented at the The 16th EASM Conference, Heidelberg.
50. Benito B, Solana J, Moreno MR. Assessing the efficiency of local entities in the provision of public sports facilities. Int J Sport Financ. 2012;7:46-72.
51. Liu YD. Sport and social inclusion: evidence from the performance of public leisure facilities. Soc Indic Res. 2009;90:325-37.
52. García-Unanue J, Felipe JL, Gallardo L. Autofinanciación en los organismos autónomos deportivos municipales en España: cálculo y evolución. Revista Española de Educación Física y Deportes. 2014;(404):15-26.
53. García-Unanue JL Felipe J, del Corral J, Gallardo L. Assessing Financial Condition of Municipal Sports Agencies: A Data Benchmarking Approach. The Open Sports Sciences Journal. 2016;9(1).
54. Zafra-Gómez JL, López-Hernández AM, Hernández-Bastida A. Evaluating financial performance in local government: maximizing the benchmarking value. Int Rev Adm Sci. 2009;75:151-67.
55. García-Unanue J, Felipe JL, Gómez-González C, del Corral J, Gallardo L. External constraints on Spanish municipal sports agencies' finances. Academia Revista Latinoamericana de Administración. 2016;29(2):198-215.
56. IHRSA. The IHRSA European Market Rrport: the size and scape of the health club industry. Boston: Club Business International; 2015
57. Bedford P. Retain & Gain: Keeping Your Members Engaged. 2009; Paper presented at the A Global Perspective: Challenges & Opportunities for Membership Growth & Retention, San Francisco.
58. LifeFitness. Estudio anual del mercado del fitness en españa 2015: Contexto, situación y tendencias del sector en España. Barcelona: Life Fitness Iberia; 2015.
59. Rodríguez-Cañamero S, López-Fernández J, Villacañas V, Gallardo AM. (2016). Evolución de los resultados del sector del fitness por tamaño de empresa. In: Gálvez Ruiz, P. et al, editors. Economía, gestión y deporte. Una visión actual de la investigación Cizur Menor: Thomson Reuters Aranzadi; 2016; p. 165-8.

Propulsive forces and their efficient application during swimming performance

Vassilios Gourgoulis[1]

This Chapter is dedicated to the memory of Prof. Robert E. Schleihauf (1948 – 2016), one of the pioneers in the estimation of the propulsive forces in swimming

When a swimmer's body is immersed into the water, the force of gravity acts on it and pulls it downward. Fortunately, the force of buoyancy pushes the body upwards, against the force of gravity, helping the swimmer to float. During swimming, when the swimmer's muscles contract to flex or to extend the joints, moving the limbs, propulsive forces are generated to displace the body forward. However, because the limbs and the body move through water, which is nearly 800 to 1000 times denser than the air, resistive forces hinder the swimmer's forward motion. Consequently, any flaw is magnified exponentially in comparison with locomotion through the air and the importance of the technique during displacement through the water increases.[1]

Although it is not existing a single "perfect" technique for all swimmers, there are principles that could be applied to be decided if a swimmer's technique is "good" or not. In this context, the forces acting on the swimmer's body should be examined. To increase forward speed, swimmers should reduce the resistive forces in comparison with the propulsive forces or overcome the resistive forces applying greater propulsive forces. However, the propulsive forces should not only be greater than the resistive forces, but should also be applied efficiently, with the least waste in effort. To be applied efficiently, the resultant propulsive force should be aimed as much as possible forward (along the desired swimming direction) and should not be wasted in other directions, giving unnecessary kinetic energy to the water.[2,3,4,5,6]

Resultant and effective force

When a swimmer's arm moves through water, at each instant of time a resultant propulsive force is produced by the swimmer's hand (Figure 1). However, not all of this force is directed horizontally forward, along the

1. Department of Physical Education and Sport Science, School of Physical Education and Sport Science, Democritus University of Thrace, Komotini, Greece

desired swimming direction. Only an amount is aimed horizontally forward, and this is the component of the resultant propulsive force in the horizontal axis, which coincides with the desired swimming direction. This component is called effective force (Figure 2).

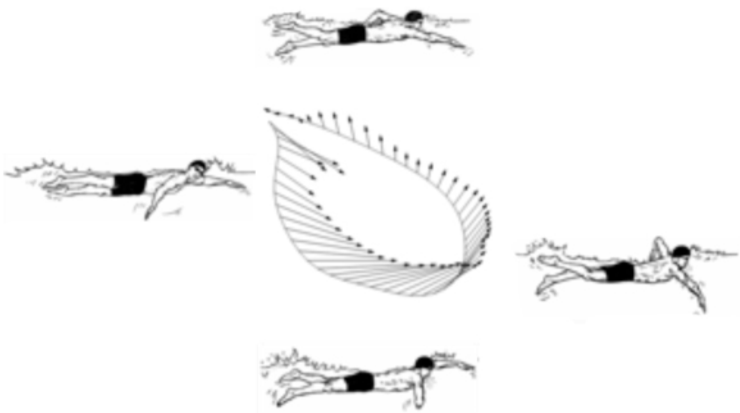


Figure 1: During an underwater arm stroke a resultant propulsive force is produced by the swimmer's hand at each instant of time.

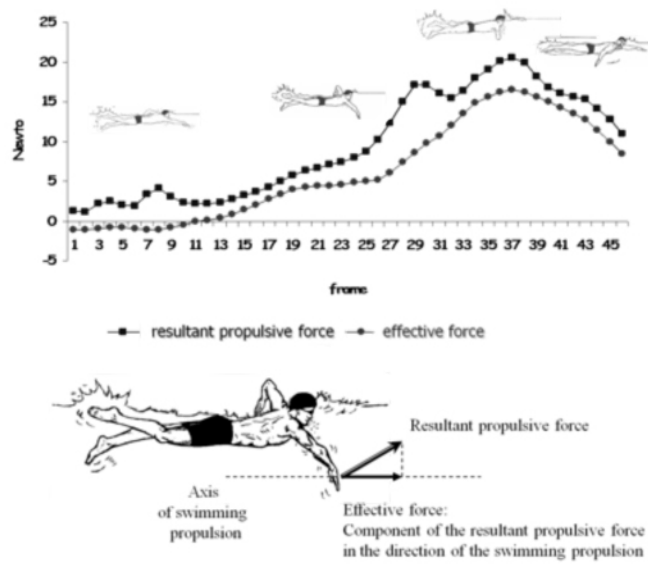


Figure 2: Not all, but only an amount of the resultant propulsive force is directed horizontally forward along the desired axis of swimming propulsion. This component is called effective force.

Swimmers should try as much as possible of the resultant force to be aimed horizontally forward, along the desired swimming direction, increasing the magnitude of the effective force.[1] The magnitude of these two forces, the resultant propulsive force and the effective force, should be as close together as possible. In this case, a great fraction of the external power produced by the swimmer's muscles is transformed into useful thrust. On the contrary, when the force generated by the swimmer is wasted in undesirable directions, the effective force is much smaller than the resultant force. An amount of force is dissipated in giving unuseful energy to the water, without contributing to propulsion, and may cause undesirable sideways and vertical deviations of the body increasing the resistive forces.[4,6]

Understanding the propulsive force

Although it is not yet quite clear the whole mechanism for the generation of the propulsive forces, it has been proved that when a swimmer's hand moves though water the pressure at the trailing (the back) side of the hand is reduced and the pressure at the leading (the palmar) side of the hand is increased. Thus, a pressure difference between the leading (high pressure area) and the trailing (low pressure area) side of the hand is formed,[7,8,9,10] which generates a complex collection of force vectors that act from the water onto the hand[11,12] and for simplifying reasons could be represented as a resultant force.[1]

To understand this resultant propulsive force it can be decomposed, as any vector, into its three perpendicular components, according to the three fingers rule of the right hand, along the X, the Y and the Z axes (Figure 3). The component of the resultant force along the X–axis is defined to be opposite to the direction of the hand movement, which is determined by its resultant velocity vector. This component is called drag force.[13] The rest two components of the resultant force along the Y and Z axes create a force vector, which is perpendicular to the drag force vector and the direction of the hand's motion. This force is called lift. Thus, the lift force vector actually has two components and lies in a plane that is perpendicular to the direction of motion.[14,15,16] Resolving the resultant force into its components (the drag and the lift forces), they can be used to understand the forces that act on a swimmer's hand (Figure 4).

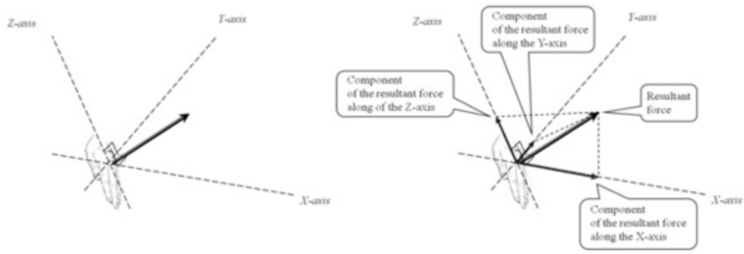


Figure 3: The resultant force vector can be projected along each axis (X, Y, Z) of the coordinate system and be decomposed into its three perpendicular components.

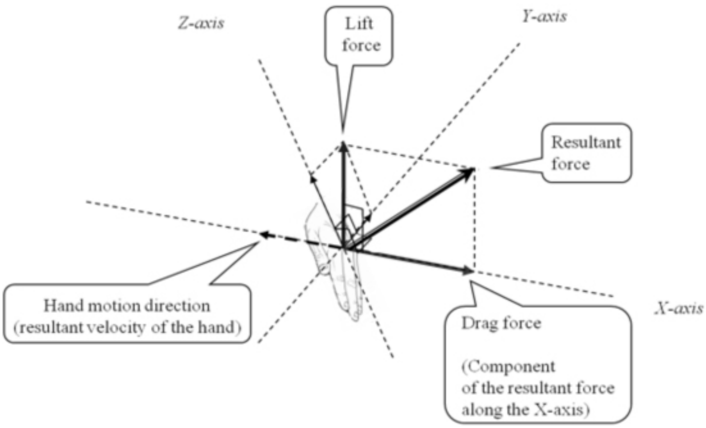


Figure 4: The resultant propulsive force vector can be resolved into the drag and the lift force. The drag force is the component of the resultant force opposite to the resultant velocity of the hand and the lift force lies in a plane perpendicular to the drag force and the resultant velocity of the hand.

During the underwater arm stroke, at each instant of time the resultant propulsive force can be broken down into these two components: the drag force and the lift force. For instance, in front crawl swimming (Figure 5), at the final part of the entry and catch phase (which lasted from the hand's entry into the water until the beginning of its backward motion), because the hand moves downward the drag force (which by definition is opposite to the direction of the hand's motion) would be aimed upward and the lift force (which by definition is perpendicular to the motion of the hand and to the drag force) would be aimed forward. At the end of the pull phase (which lasted from the beginning of the hand's backward motion until the time where the hand crosses the transverse plane passing through the shoulder joint), because the hand moves backward and slightly upward, the drag force would be aimed forward and slightly downward, and the lift force would be aimed upward and slightly forward. At the final part of the push phase (which lasted from the end of the pull phase until the hand's exit out of the water), because the hand moves upward, the drag force would be aimed downward, and the lift force would be aimed forward. The resultant propulsive force is always a combination of the drag and the lift propulsive forces.[13,16,17,18]

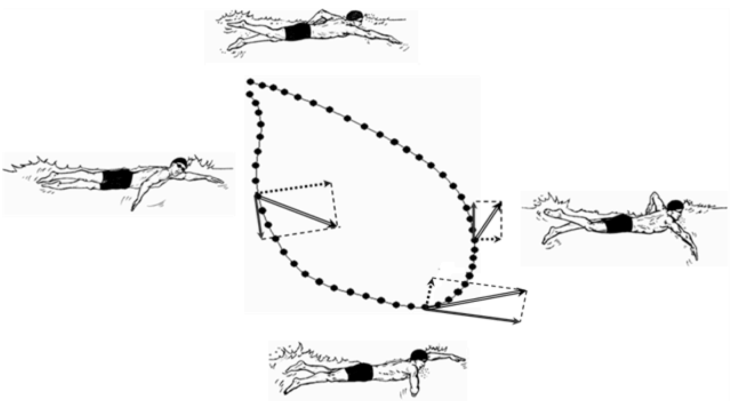


Figure 5: At each instant of time the resultant propulsive force (vector with double line) can be decomposed into two components: the drag (vector with solid line) and the lift force (vector with dashed line).

The drag force

The drag force is by definition opposite to the direction of the motion of a limb. This means that, for instance, when the hand moves backward the drag force would be directed forward. At each instant of time, the direction of hand's motion is determined by the direction of the resultant velocity vector of the hand and thus, the drag force is always opposite to the direction of hand's velocity vector.[13]

The faster the motion of the hand and the bigger the surface area of the hand, the greater is the drag force acting in the opposite direction of the hand's motion, because according to the hydrodynamic equation (1), the drag force is proportional to the square of the resultant velocity of the hand and the surface area of the hand:

$$F_{DRAG} = \frac{1}{2} \cdot C_{DRAG} \cdot \rho \cdot v^2 \cdot S \qquad (1)$$

where, ^{C}DRAG is the hydrodynamic coefficient of drag, ρ is the density of the water, v is the hand's resultant velocity and S is the surface area of the hand.

The lift force

The lift force lies by definition in a plane perpendicular to the direction of the hand's motion and the drag force vector,[15,16] and thus is always perpendicular to the direction of the flow passing the moving hand.[13]

Similar to the drag force, the faster the motion of the hand and the bigger the surface area of the hand, the greater is the lift force that is acting perpendicular to the hand's motion, because according to the hydrodynamic equation (2), the lift force is proportional to the square of the resultant velocity of the hand and the surface area of the hand:

$$F_{LIFT} = \frac{1}{2} \cdot C_{LIFT} \cdot \rho \cdot v^2 \cdot S \qquad (2)$$

where, C_{LIFT} is the hydrodynamic coefficient of lift, ρ is the density of the water, v is the hand's resultant velocity and S is the surface area of the hand.

The direction of the resultant propulsive force

As it is already mentioned, when the swimmer's hand moves through water, the direction of its motion is determined by its resultant velocity vector and due to the pressure difference between the leading and the trailing side of the hand a resultant propulsive force is created. This force can be decomposed into three components. The force component opposite to the resultant velocity vector of the hand (and the direction of the motion of the hand) is called drag force. The other two components can be composed into the lift force vector, which by definition lies always in a plane perpendicular to the drag force vector and the resultant velocity vector of the hand. Thus, for reductive, simplifying and understanding reasons, the force generated by a swimmer's hand can be resolved into the drag and the lift propulsive forces.[1] However, actually, the swimmers did not and cannot feel the drag and the lift forces. They feel only the resultant force, due to the differential pressure.[7] Moreover, this approximation is a "quasi-steady state" approach, where it is assumed that the motion of the hand and the water flow velocity is constant and it is not taken into account the unsteady nature of the swimmer's propulsion,[5,9,13,14,16,18] as will be discussed in detail at the end of this chapter.

For an efficient arm stroke, the resultant propulsive force should be aimed as much as possible horizontally forward, along the desired swimming direction, while forces acting in other directions are inefficient, require an amount of energy without contributing to propulsion, and may cause undesirable sideways and vertical deviations of the body increasing the resistive forces.[4,6]

Consequently, two questions arise:

- *On what depends the direction of the resultant propulsive force?*
- *How can a swimmer modify the direction of the resultant propulsive force to be aimed mainly horizontally forward?*

During an arm stroke, at each instant of time, the lift force is perpendicular to the drag force and the resultant propulsive force is the vector sum of the drag and the lift force vectors. Thus, modifying appropriately the magnitude and the relative contribution of the drag and the lift force vectors changed also the direction of their resultant force[18] (Figure 6).

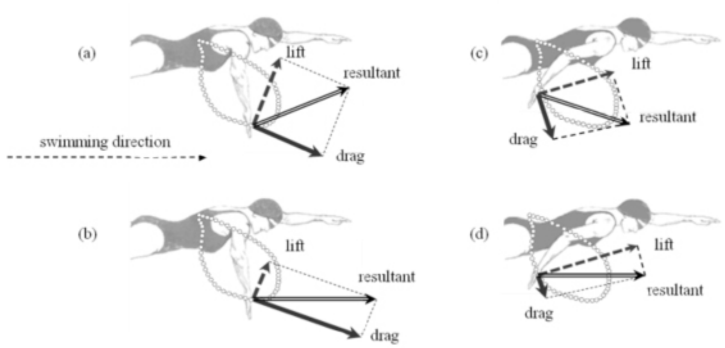


Figure 6: Modifying appropriately the magnitude and the relative contribution of the drag and lift force vectors changed also the direction of their resultant force (a and b: during the pull phase; c and d: during the push phase) (modified from Gourgoulis et al.[18]).

The next question arises is:

- *How can a swimmer modify the relative contribution of the drag and lift force?*

To answer this question, the parameters that determine the magnitude of the drag and lift forces should be examined. According to the hydrodynamic equations (1) and (2), the drag and the lift force depend on the density of the water (ρ), the surface area of the hand (S), the square of the hand's resultant velocity (v^2) and the hydrodynamic coefficient of drag (^{C}DRAG) and the hydrodynamic coefficient of lift (^{C}LIFT), respectively.

For a swimming pool the density of the water (ρ) is given and for a particular swimmer the surface area of the hand (S) is also unchangeable, unless hand paddles are used, which increase the pulling surface of the hand. However, their use is not allowed in competition. The resultant velocity of the hand (v) can be changed, but this modification would affect both the drag and the lift forces to the same extent. Thus, the only remaining tool is to manage properly the drag and lift hydrodynamic coefficients.[18]

Both coefficients depend on the inclination and the orientation of the hand, which is determined by two angles: the pitch angle and the sweepback angle of the hand.[13]

The pitch angle of the hand

The pitch angle, which is also called "angle of attack", is the angle formed between the plane of the hand and the resultant velocity vector of the hand, which determines the direction of motion of the hand[13,19,20] (Figure 7).

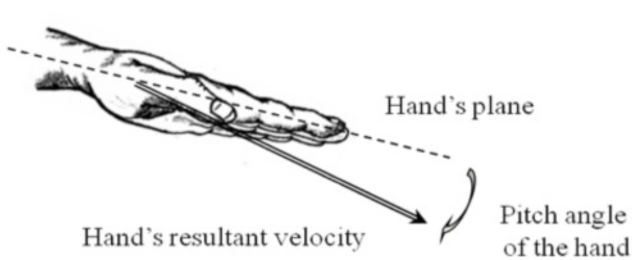


Figure 7: The pitch angle of the hand is the angle between its plane and its resultant velocity vector.

In swimming, during the underwater motion of the hand, at each instant of time the inclination of the plane of the hand is changed, as well as the direction of its resultant velocity vector. Consequently, the pitch angle of the hand is also changed. For instance, in front crawl, during the entry and catch phase the pitch angle is small, during the pull phase it is large and during the final part of the push phase it becomes small again[21] (Figure 8).

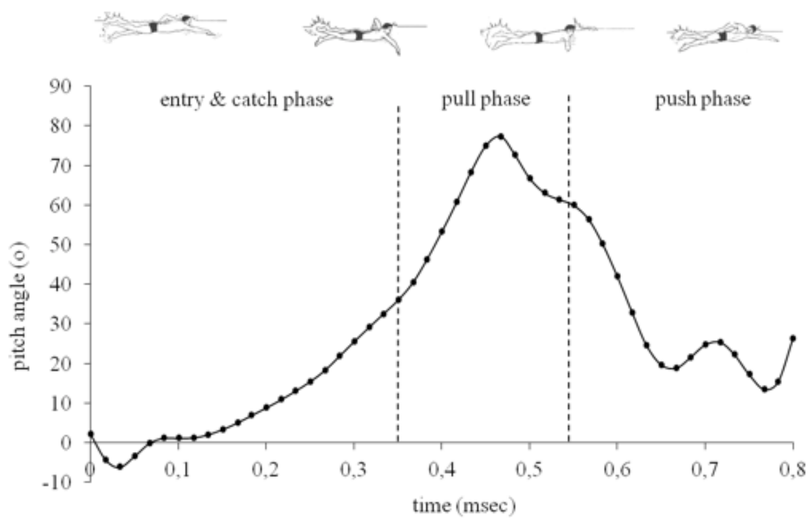


Figure 8: In front crawl swimming, during the entry and catch phase the pitch angle is small, during the pull phase it is large and during the end of the push phase it becomes small again.

The sweepback angle of the hand

The sweepback angle defines the leading edge of the hand motion, projecting the hand's resultant velocity vector onto its plane. For instance, when the thumb side leads the hand motion the sweepback angle is zero (0) degrees, when the fingertips lead the motion the sweepback angle is 90 degrees, when the little finger side leads the motion the sweepback angle is 180 degrees and when the wrist leads the hand motion the sweepback angle is 270 degrees[13,19,20] (Figure 9).

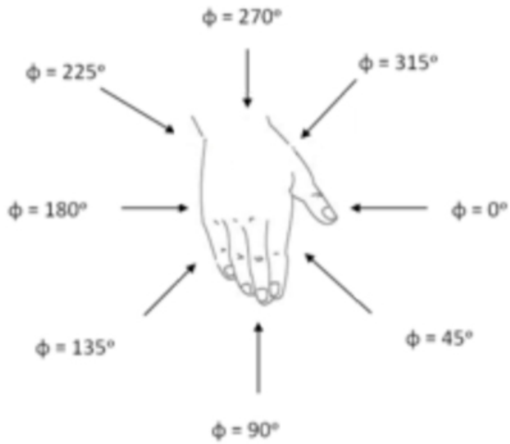


Figure 9: The sweepback angle of the hand defines the leading edge of the hand motion.

During the arm stroke, for instance in front crawl swimming, the sweepback angle is continuously changed, because different sides of the hand lead the motion, and thus the sweepback angle varies (Figure 10).

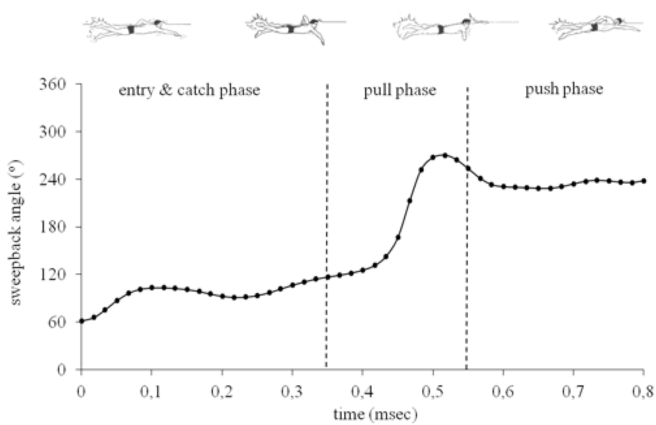


Figure 10: The sweepback angle varies during the underwater arm stroke in front crawl swimming because different sides of the hand lead the motion.

The hydrodynamic coefficients of the hand

The hand's hydrodynamic coefficients are dimensionless quantities, which depend mainly on the inclination (pitch angle) and the orientation (sweepback angle) of the hand.

Schleihauf[13] measured the forces acting onto a hand model and, using the hydrodynamic equations (1) and (2), determined drag and lift hydrodynamic coefficients for discrete inclinations and orientations of the hand model under steady – state conditions, in which the water flow velocity was constant. The values of these coefficients are presented as curves versus pitch angle for discrete sweepback angles of the hand (Figure 11).

However, it seems that Scheihauf[13] decomposed the resultant force in only two dimensions and calculated hydrodynamic coefficients for the drag force and only one of the two lift force components. Schleihauf's work was extended by Berger et al.[15] and Sanders[16] calculating hydrodynamic coefficients for all three components of the resultant force. Furthermore, Sanders[16] presented the drag and the two lift hydrodynamic coefficients as continuous three-dimensional surfaces, enabling a more accurate determination of the coefficients' values for any possible pitch and sweepback angle during actual swimming (Figure 12).

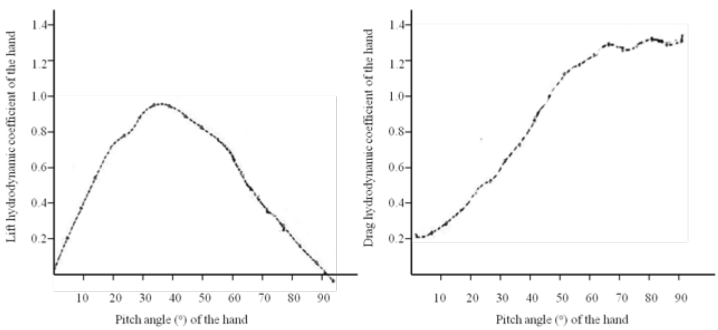


Figure 11: Lift and drag hydrodynamic coefficients of the hand versus the pitch angle of the hand (0 to 90 degrees) for a given sweepback angle of 45 degrees (modified from Schleihauf[13]).

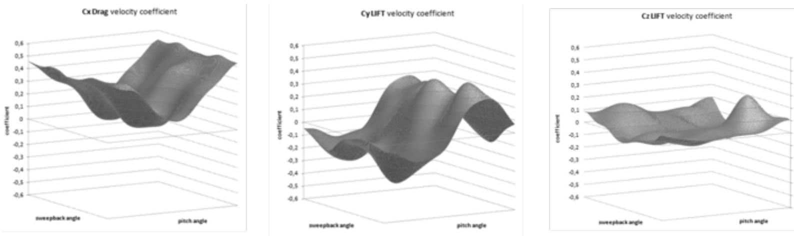


Figure 12: Three-dimensional surfaces of the hand's hydrodynamic coefficients for the drag force and the two components of the lift force, as function of the pitch (-90 to 90 degrees) and the sweepback angle (0 to 360 degrees) of the hand (modified from Sanders[16]).

Observing these coefficients, despite the discrepancies in their magnitude, arises that when the pitch angle of the hand takes high values, the values of the drag hydrodynamic coefficient are high. This means, for instance, that during an underwater arm stroke when the plane of the hand is almost perpendicular to the direction of the motion of the hand, and the hand "presses" the water, the drag force values would be high. On the contrary, when the pitch angle of the hand is small to medium, and the hand "slices" through the water, the drag force generated by the hand would be small. Concerning the values of the lift hydrodynamic coefficients it appears that when the pitch angle of the hand takes high values, the lift force values are low, while at small to medium pitch angles, where the hand "slices" through the water, the lift force generated by the hand is large.

To understand the major role and the importance of the pitch angle of the hand on the magnitude of the drag and the lift hydrodynamic coefficients and consequently on the magnitude and the relative contribution of the drag and lift forces, a very simple experiment could be done. Driving a car, if someone stretch his or her arm out of the window, holding the hand with the palm faced downward at a pitch angle of near zero (0) degrees, the drag force of the air will push the hand and arm slightly backward, without any elevation. This means that no lift force would be experienced. If the pitch angle of the hand is changed with the palm facing the direction of car's motion to about 35 degrees, an increase in pressure in the palmar side of the hand takes place and the magnitude of both the drag and lift force components acting on the hand will increase. Now the hand will be pulled back even more than before, due to the increased drag force component, while simultaneously the lift force component will push the hand upwards. If the pitch angle of the hand is changed to minus 35 degrees, the air above the back side of the hand will have an increase in pressure, and the air pressure on the palmar side of the hand will be decreased. Now, the lift force component acting on the hand will be aimed downward, and the hand will move downward and backward. If the hand is holding at a pitch angle of 90 degrees, only the drag force of the air will push the hand and arm much more backward than before, and no lift force will be experienced. So, it is obvious that large pitch angle results in the generation of a large drag force, while a medium to small pitch angle results in a large lift force.[1, 22]

From the above it is concluded that, since the magnitude of the drag and lift hydrodynamic coefficients depend on the orientation and the inclination of the hand, changing the sweepback and, especially and more importantly, the pitch angle of the hand, changed also the magnitude and the relative contribution of the drag and lift forces.

The question arises now is:

- *Why is it so important to know which of the two forces, the lift or the drag force, makes the greater contribution to propulsion?*

The stroking pattern

The knowledge of the type of the propulsive force, the drag or the lift force, with the greater contribution has significant implications for swimming technique, because it determines the emphasis of the propulsive movements during the stroke and consequently the movement pattern that should be used.1 If the drag force has the greater contribution to propulsion the stroking pattern should be primarily backwards and the swimmers should "press" the water with their hands using large pitch angles. If the lift force has the greater contribution the emphasis should be given to large lateral and vertical movements and the swimmers should "sweep" their hands with small pitch angles.[11]

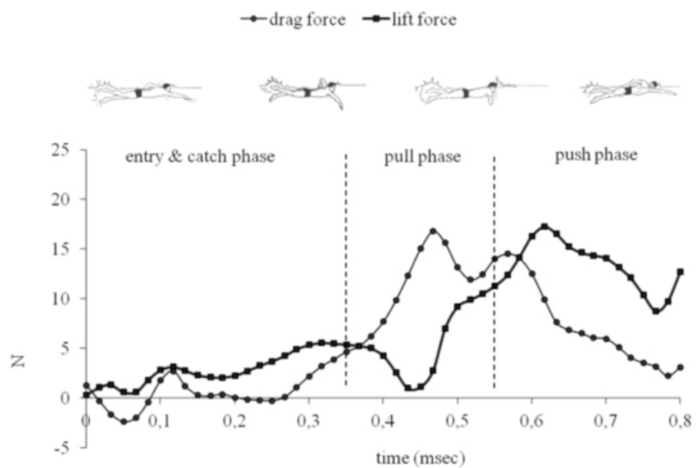
It is observed that high-skilled swimmers pull their hands primarily diagonally backwards against the water, rather than emphasize lateral movements, in all strokes other than breaststroke.[2,16] Even in breaststroke, during the in-sweep phase a diagonally in and slightly backward motion results in a better and more efficient orientation of the resultant force forward, along the swimming direction, in comparison with a pure inward motion.[13] When the hand moves backwards with a large pitch angle the drag force is the major contributor to the resultant force generated by the hand. On the contrary, the contribution of the lift force is maximized when the pitch angle of the hand reaches medium values. However, even then, the contribution of the drag force is also important as the contribution of the lift force.

Nevertheless, even though the stroking pattern of the hand should be predominantly backward, swimmers do not and should not move their hands exactly straight backwards. The stroking pattern aims not only to create propulsive forces, but also to counteract rotational forces. Thus, there is always some element of sideways movements that occur to satisfy reaction accommodations, for instance, due to breathing, the body roll and/or the recovering of the other arm. Moreover, a small amount of sideways movements contributes in a more effectively use of the muscle and lever systems, increases the propulsive impulse lengthening the distance travelled by the hand and helps to continually find still water to accelerate backwards.[2,11,23,24]

To become efficient, for instance during front crawl swimming, swimmers should navigate their arms in such a manner that their palms should always face toward their feet and actually “press” the water with their hands primarily backwards with large pitch angles during the middle part of the stroke and “sweep” their hands diagonally backward, outward and upward, with small pitch angles and with a little-finger-ward out sweep motion during the final part of the underwater arm stroke.[25,26] Pitching their hands with such a manner, in the middle part of the stroke, during the pull phase, swimmers are taking advantage of drag forces, with a smaller contribution of the lift forces, due to the larger pitch angle of the hand, and in the final part of the stroke, during the push phase, they generate more lift than drag force, due to the smaller pitch angle of the hand.[2,11,18,23,24] With such navigation of the hand, the resultant force would be aimed more in the desired direction (forward) and the effective force would not be much smaller than the resultant force (Figure 13).

Consequently, in all swimming strokes other than breaststroke, swimmers should try to “press” the water primarily backwards toward their feet and slightly diagonally outward, without a big and exaggerated “S”- shaped pulling pattern (Figure 14). A slight “S” is acceptable, but large sweeping motions, emphasizing lateral movements, should be avoided,[2,27] whereas in front crawl it is suggested that as the race distance decreases and the swimming speed becomes more important, a straighter arm pull should be adopted.[28] The resultant force is always a combination of drag and lift forces, but their relative contribution changes along the stroke, while the statement of the overall domination of the drag or the lift force is an oversimplification.[18]

(a)



(b)

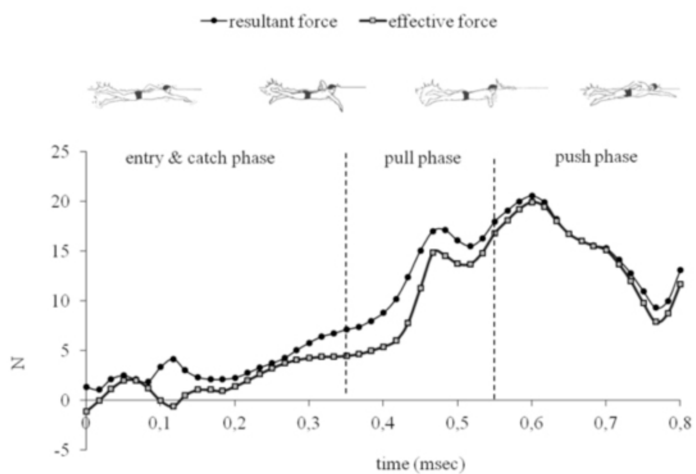


Figure 13: (a) Relative contribution of the drag and lift force in front crawl swimming. (b) Resultant and effective force in front crawl swimming.

Figure 14: Stroke pattern in front crawl swimming relative to swimmer's body. For an efficient application of the propulsive forces in front crawl the swimmers should "press" the water primarily backwards and slightly diagonally outward, without emphasizing lateral movements.

Summarizing …

Question: How can a swimmer modify the direction of the resultant force to be aimed mainly horizontally forward?

Answer: Modifying appropriately the magnitude and the relative contribution of the drag and lift forces.

Question: How can a swimmer modify the relative contribution of the drag and the lift forces?

Answer: Modifying the inclination and orientation of the hand, by changing the pitch and the sweepback angle of the hand.

Question: How can a swimmer modify appropriately the pitch and the sweepback angle of the hand?

Answer: Using an arm stroke pattern in a predominantly backward direction.

Limitations and perspectives

The most popular procedure for estimating the propulsive forces generated by a swimmer's hand uses a combination of kinematic data derived from underwater three-dimensional kinematic analysis of the hand's movement and predetermined hydrodynamic coefficients for the hand obtained from water channel experiments with hand models. Calculating, from the kinematic data, the pitch and the sweepback angles of the swimmer's hand at each instant of time during an underwater stroke, it is possible to determine the values of the drag and lift hydrodynamic coefficients, and using the hydrodynamic equations (1) and (2) to estimate the magnitude of the drag and lift forces, the magnitude and the direction of their resultant force and the magnitude of the effective force.

However, using this approach there are a lot of limitations. Although the directions of the drag and the lift forces can be determined with accuracy, their exact magnitude is not easy to be specified.[11] The drag and lift forces are not measured directly. Instead, they are estimated indirectly from kinematic data and specific hydrodynamic coefficients. Therefore, there are some errors derived from the calibration of the recorded space, from the distortion during underwater recordings, from the digitizing of the selected points onto the hand and from the calculation of pitch and sweepback angles of the hand.[15,16,18] Moreover, the magnitude of the hydrodynamic coefficients is not only a function of the pitch and the sweepback angles of the hand, but also depends on the shape of the hand's model and the position of the fingers (especially the position of the thump).[29,30]

Using the above mentioned methodology to estimate the propulsive forces produced by a swimmer's hand, which is called the "quasi-steady state" approach,[13,14] it is assumed that the flow under steady conditions in a water channel is comparable to the flow during actual swimming.5 Moreover, only the hand's speed, inclination and orientation relative to the flow were considered,[9] while the time-variant properties of force generating mechanisms are ignored.[31] It is assumed that the overall flow field does not change very quickly with time. However, swimmers do not move their hands and arms in steady conditions. Their stroke paths are usually curved[9,32] and their propelling segments accelerate, decelerate and change their orientation, as they move through water. This means that their motion, and consequently the water flow around them, is unsteady. Thus, the "quasi-steady state" hydrodynamic theory is insufficient to describe the mechanisms by which humans propel themselves through water.[12,33] The propulsive forces generated by a swimmer's hand depend not only upon the size, the shape, the inclination, the orientation and the velocity of the hand, but also the effects of the acceleration should be taken into account.[23,32,34,35] Sanders[16], by measuring the forces acting on an accelerating hand showed that accelerations have large effects on the total force and so must be considered in addition to the instantaneous speed when estimating forces from time records of hand motion. When the supplementary forces due to the acceleration of the hand are considered the estimated magnitude of the propulsive forces increased.[18] On the contrary, when the acceleration of the hand is not included, as in the “quasi–steady state” approach, these additional forces are neglected.[36]

Moreover, in the “quasi–steady state” approach, the forces produced due to the vortex production and the rotation of the arm are not considered. However, when a swimmer’s hand moves though water, trailing vortices are created at the back side of the hand and detached from the hand’s surface. These vortices, because of the high circulation of the water, increase the flow velocity enhancing the reduction of the water pressure behind the hand.[7,9,12] A remarkable amount of momentum is generated through this process of vortex production and shedding, and swimmers can generate unsteady forces in addition to the steady forces.[8,12] Moreover, due to the fact that the arm movement is not only a translation through water, but instead is mainly a complicated combination of translation and rotation, the tangential velocity near the hand is higher than near the elbow and near the shoulder, causing a velocity gradient of the water close to the limb. This induces an accelerating axial water flow component and an axial pressure gradient along the arm and hand towards the fingertips, which seems to be more abrupt at the trailing than at the leading side of the limb. Due to this axial pressure gradient, the local pressure of the affected water close to the limb is decreased towards the fingertips and the circumferential pressure difference between the leading (high pressure area) and the trailing (low pressure area) side of the hand, due to its translational movement, is enhanced increasing the magnitude of the propulsive forces.[10]

Furthermore, most of the attention has been paid to what the hand does. However, the forearm,[35,37] and even the lower part of the upper arm,[38] provide also effective propelling surfaces and their contribution on the propulsive forces should also be considered.

Studying the water’s behaviour in the wakes and measuring its flow around a swimmer’s limb or the whole body, it is likely to understand the resulting forces that are generated. Thus, more sophisticated methods, like Computational Fluid Dynamics (CFD), Particle Image Velocimetry (PIV) and SWimming hUman Model (SWUM), should be used to understand how the water reacts to the swimmer’s movements. CFD is a numerical simulation technique to study the fluid flow, PIV is a quantitative flow visualization method that can be used to provide measurements of the instantaneous velocity vectors and related properties, such as normal and shear stress, in actual fluids and SWUM is a simulation model, which considers rigid body dynamics and unsteady fluid forces for the whole body. Although these methods have also some limitations and demerits,[9] combining the findings from CFD, PIV and SWUM, in conjunction with direct pressure measurements, could help researchers, coaches and swimmers greatly in visualizing and understanding the complicated fluid dynamic mechanisms that generate propulsive forces in human swimming.[9,12,33]

References

1. Schleihauf RE. Biomechanics of Human Movement. Bloomington, Indiana: AuthorHouse; 2004.
2. Rushall BS, Sprigings EJ, Holt LE, Cappaert JM. A Re-evaluation of forces in swimming. J Swim Res. 1994; 10: 6–30.
3. Sato Y, Hino T. A computational fluid dynamics analysis of hydrodynamic force acting on a swimmer's hand in a swimming competition. J Sport Sci Med. 2013; 12: 679–689.
4. Toussaint HM, Hollander AP, Berg Cvd, Vorontsov AR. Biomechanics of swimming. In: Garrett WE, Kirkendall DT, editors. Exercise and Sport Science. Philadelphia, Lippincott: Williams & Wilkins, 2000; p. 639–660.
5. Toussaint HM, Truijens M. Biomechanical aspects of peak performance in human swimming. Anim Biol. 2005; 55(1): 17–40.
6. Vorontsov AR, Rumyantsev VA. Propulsive forces in swimming. In: Zatsiorsky VM, editor. Biomechanics in Sport – Performance, enhancement and injury prevention. Oxford: Blackwell Science, 2000; p. 205–231.
7. Arellano R. Vortices and propulsion. In: Sanders R, Linsten J, editors. Swimming: Applied Proceedings of the XVII International Symposium on Biomechanics in Sports. Perth, Western Australia: School of Biomedical and Sports Science, 1999; p. 53–66.
8. Matsuuchi K, Miwa T, Nomura T, Sakakibara J, Shintani H, Ungerechts BE. Unsteady flow field around a human hand and propulsive force in swimming. J Biomech. 2009; 42(1): 42–47.
9. Takagi H, Nakashima M, Sato Y, Matsuuchi K, Sanders RH. Numerical and experimental investigations of human swimming motions. J Sports Sci. 2016; 34(16): 1564–1580.
10. Toussaint HM, Den Berg CV, Beek WJ. "Pumped-up propulsion" during front crawl swimming. Med Sci Sports Exerc. 2002; 34: 314–319.
11. Maglischo EW. Swimming fastest. Champaign IL: Human Kinetics; 2003.
12. Takagi H, Nakashima M, Ozaki T, Matsuuchi K. Unsteady hydrodynamic forces acting on a robotic arm and its flow field: Application to the crawl stroke. J Biomech. 2014; 47(6): 1401–1408.
13. Schleihauf RE. A hydrodynamic analysis of swimming propulsion. In: Terauds J, Bedingfield EW, editors. Swimming III. International Series of Sports Science, Vol. 8. Baltimore, MD: University Park Press, 1979; p. 70–117.
14. Berger MAM, De Groot G, Hollander AP. Hydrodynamics drag and lift forces on human hand/arm models. J Biomech. 1995; 28(2): 125–133.
15. Berger MAM, Hollander AP, De Groot G. Determining propulsive force in

front crawl swimming: A comparison of two methods. J Sports Sci. 1999; 17: 97–105.
16. Sanders RH. Hydrodynamic characteristics of a swimmer's hand. J Appl Biomech. 1999; 15: 3–26.
17. Gourgoulis V, Aggeloussis N, Vezos N, Kasimatis P, Antoniou P, Mavromatis G. Estimation of hand forces and propelling efficiency during front crawl swimming with hand paddles. J Biomech. 2008; 41: 208–215.
18. Gourgoulis V, Boli A, Aggeloussis N, Antoniou P, Toubekis A, Mavrommatis G. The influence of the hand's acceleration and the relative contribution of drag and lift forces in front crawl swimming. J Sports Sci. 2015; 33(7): 696–712.
19. Schleihauf RE, Gray L, De Rose J. Three – dimensional analysis of hand propulsion in the sprint front crawl stroke. In: Hollander AP, Huijing PA, de Groot G, editors. Biomechanics and Medicine in Swimming. Champaign, IL: Human Kinetics Publishers, 1983; p. 173–183.
20. Gourgoulis V, Antoniou P, Aggeloussis N, et al. Kinematic characteristics of the stroke and orientation of the hand during front crawl resisted swimming. J Sports Sci. 2010; 28(11): 1165–1173.
21. Gourgoulis V, Aggeloussis N, Vezos N, Antoniou P, Mavromatis G. Hand orientation in hand paddle swimming. Int J Sports Med. 2008; 29: 429–434.
22. Sprigings EJ, Koehler JA. The choice between Bernoulli's or Newton's model in prediciting dynamic lift. Int J Sport Biomech. 1990; 6: 235–245.
23. Bixler B. Resistance and propulsion. In: Stager JM, Tanner DA, editors. Swimming. Oxford, UK: Wiley-Blackwell Scientific Publications Limited, 2005; p. 59–101.
24. Sanders RH. Lift performance in aquatic sports. In: Riehle HJ, Vieten MM, editors. Proceedings XVI International Symposium of Biomechanics in Sports. Germany: University of Konstanz, 1998; p. 25–39.
25. Marinho DA, Barbosa TM, Kjendlie PL, et al. Swimming Simulation: A new tool for swimming research and practical applications. In: Peters M, editor. Computational fluid dynamics for sport simulation. Lecture Notes in Computational Science and Engineering 72. Berlin Heidelberg: Springer-Verlag, 2009; p. 33–61.
26. Riewald S, Bixler B. CFD analysis of a swimmer's arm and hand acceleration and deceleration. In: Blackwell J, editor. XIX International Symposium on biomechanics in sports. San Francisco: University of San Francisco, 2001; p. 117–121.
27. von Loebbecke A, Mittal R. Comparative analysis of thrust production for distinct arm-pull styles in competitive swimming. J Biomech Eng. 2012; 134(7): 074501-1 – 0745501- 4.
28. Nakashima M, Maeda S, Miwa T, Ichikawa H. Optimizing simulation of the arm stroke in crawl swimming considering muscle strength characteristics of athlete swimmers. J Biomech Sci Eng. 2012; 7(2): 102–117.
29. Marinho DA, Rouboa AI, Alves FB, et al. Hydrodynamic analysis of different thumb positions in swimming. J Sport Sci Med. 2009; 8: 58–66.
30. Marinho DA, Barbosa TM, Reis VM, et al. Swimming propulsion forces are enhanced by a small finger spread. J Appl Biomech. 2010; 26: 87–92.
31. Dickinson MH. Unsteady mechanisms of force generation in aquatic and

aerial locomotion. Am Zool. 1996; 36: 537–554.
32. Bixler B, Schloder M. Computational Fluid Dynamics: An analytical tool for the 21th century swimming scientist. J Swim Res. 1996; 11: 4–22.
33. Takagi H, Shimada S, Miwa T, Kudo S, Sanders R, Matsuuchi K. Unsteady hydrodynamic forces acting on a hand and its flow field during sculling motion. Hum Mov Sci. 2014; 38: 133–142.
34. Pai Y-C, Hay JG. A hydrodynamic study of the oscillation motion in swimming. Int J Sport Biomech. 1988; 4: 21–37.
35. Rouboa A, Silva A, Leal L, Rocha J, Alves F. The effect of swimmer's hand/forearm acceleration on propulsive forces generation using computational fluid dynamics. J Biomech. 2006; 39: 1239–1248.
36. Kudo S, Vennell R, Wilson B. The effect of unsteady flow due to acceleration on hydrodynamic forces acting on the hand in swimming. J Biomech. 2013; 46: 1697–1704.
37. Bixler B, Riewald S. Analysis of a swimmer's hand and arm in steady flow conditions using computational fluid dynamics. J Biomech. 2002; 35: 713–717.
38. Lecrivain G, Slaouti A, Payton C, Kennedy I. Using reverse engineering and computational fluid dynamics to investigate a lower arm amputee swimmer's performance. J Biomech. 2008; 41: 2855–2859.

Hyperthermia and dehydration in competitive swimmers: current aspects and recommendations

Orlando Laitano[1],[2], Lara Elena Gomes[1], Alex J. Mattingly[2] and Flávio Antônio de Souza Castro[3]

Introduction

Swimming is one of the most popular Olympic sports, with individual events in freestyle, backstroke, breaststroke, butterfly and medley. In addition to these individual events, Olympic swimmers also participate in freestyle and medley relays. The distances covered by a swimmer in the aforementioned events range from 50 to 1500 m. In addition to these events, since the Olympic Games in Beijing 2008, open water swimming became an official event and its popularity has increased since then with an explosion in global participation and the number of competitive events. For instance, in London 2012 open water swimming was part of the Olympic program, but as a swimming event. At the Rio 2016 Games, open water swimming was considered a standalone modality, evidencing the world popularity it has achieved in the last few years.

The distances covered by open water swimmers at the International Swimming Federation (FINA) World Championships vary from 5, 10 (Olympic distance) to 25 km. The 10 km event is described as the aquatic equivalent of the marathon run and the duration of this event ranged from 110 to 130 min for males and from 119 to 137 min for females' elite open water swimmers at the FINA/HOSA 10 km Marathon Swim. (World Cup 2016 on Balatonfüred, Hungary). The open water events also attract recreational swimmers who enjoy the challenges of prolonged physical exertion mixed with unpredictable environmental conditions that are not found in the controlled climate of the indoor swimming pool.

In spite of this, hyperthermia and dehydration are hardly considered a problem in swimming even though training and competition, in many times, involve prolonged high-intensity exercise[1]. Therefore, the aims of

1. Physical Education Collegiate, Federal University of Vale do São Francisco, Petrolina/PE, Brazil
2. Department of Applied Physiology and Kinesiology, University of Florida, Gainesville/FL, USA
3. Aquatic Sports Research Group, Federal University of Rio Grande do Sul, Porto Alegre/RS, Brazil

our chapter are: 1) to provide a summary of studies that have addressed the issue of heat stress and fluid balance in swimmers; 2) to broaden the framework of discussion regarding heat stress and fluid balance in swimmers to incite new studies addressing the unresolved issues in this field; and 3) to provide evidence-based recommendations to coaches and athletes to prevent hyperthermia and dehydration in swimming.

Hyperthermia in swimming

Skeletal muscle contraction increases metabolic heat production in an intensity-dependent manner, which elevates core temperature[2]. When exercise is performed on land, evaporation of sweat represents the main mechanism by which the body maintains internal temperature within physiological range[3]. However, during exercise in water, there is little possibility for evaporative heat loss because most of the body is immersed in water; the areas of skin surface that are exposed to air are wet, therefore sweat secretion would have a small contribution for thermoregulation[4]. The main mechanisms for thermoregulation in swimming are convection and conductance and therefore body's ability to maintain core temperature is dependent mainly upon water temperature as water is a more effective medium than air for convective heat transfer due to its heat-transfer coefficient that is ~25 times greater than air[5, 6]. In Figure 1 we report the main sources of heat gain and losses in swimming as compared to land-based sports. Although the number of heat gain sources is similar between them, the number of heat loss pathways is fewer in outdoor swimming.

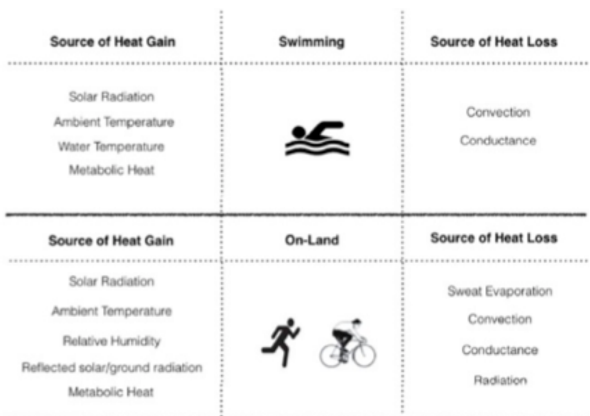


Figure 1. Sources of heat gain/loss in outdoor/open water swimming versus on-land outdoor sports.

While in indoor and some outdoor swimming pools the water is typically kept under controlled temperatures, which reduces the risk of hyperthermia, during open water swimming the water temperature depends on the environmental conditions. A recent study demonstrated that swimming at a water temperature of 33 °C was ineffective to induce heat acclimation and was not ergogenic for swimmers[7]. When water temperature is above skin temperature (~32-33 °C at rest) there will be heat gain by the body[6]. In this regard, FINA has determined in 2013 a water temperature limit of 31 °C for official open water swimming races for safety reasons[8]. Nevertheless, ambient temperature is not the only factor that may increase the risk of hyperthermia in outdoor swimmers. For instance, radiation has recently been shown to reduce exercise performance[9] and could be an additional factor that affects open water swimmers' performance and those whose practices and races are performed in outdoor swimming pools.

Likewise, under higher swimming intensities, metabolic heat production will also increase body temperature. For example, if 1 L of O2 consumed generates about 20 kJ of heat, a swimmer with a VO2max of 50 ml/kg/min and body mass of 70 kg, swimming at an intensity correspondent to 75% of VO2max, will generate ~3120 kJ (~750 kcal) of metabolic heat/h of activity excluding environmental heat sources. Regarding the intensity, along a 10 km open water event, heart rate was registered as 141 ± 5 bpm, for adults with 24.4 ±36 years old15. Thus, given that an average competitive open water swimmer races for ~2 h in the 10 km event, one can estimate that metabolic heat production in combination with increased water temperature will result in hyperthermia that may hamper performance and risk athletes' health.

There are reports of deaths due to heat illness during open water swimming. During the 2010 FINA 10-km open-water World Cup in Fujairah (Dubai), an elite athlete of team USA died[10]. Although medical details of the autopsy have not been released, concerns have been raised about the water temperature during the swimming competition[11]. FINA officials claim that the water temperature exceeded 31 °C (near its finish at 11:30 AM). Furthermore, intriguing data indicate that the majority of deaths in triathlon occur during the swim phase[12, 13]. The prevalence of deaths by heat illness in swimming (e.g. open water swimming) is likely to be underestimated[14] because drowning is ultimately what leads to death. As discussed in the next section, there has been a high prevalence of dehydration in swimmers during practices as demonstrated by changes in body mass, elevated urine osmolality and/or specific gravity[15, 16] and this may be another factor involved in the increased risk of heat-related illnesses in swimmers.'

Dehydration in swimming

In exercise settings, significant increase in core temperature leads to sweat-induced dehydration and hampers physical performance[17]. There has been considerable interest in the effects of dehydration, defined as acute reductions greater than 2% of body mass, on exercise performance, and it has been fairly well established that higher levels of sweat-induced dehydration can limit exercise performance[17,18]. However, because sweating is not the main thermoregulatory pathway during swimming, it is not entirely clear what swimmers' sweat electrolyte composition and rate are. This information might be of great help to sports dietitians to guide fluid replacement in swimmers. Likewise, whether dehydration affects swimming performance remains a matter of debate. Surprisingly, a rather limited number of studies have addressed these questions because sweat electrolyte composition assessment is particularly challenging in swimming settings.

In comparison with exercise on land, it is puzzling to define sweat electrolyte composition in swimmers while in the swimming pool. In studies where sweat electrolyte composition is determined, absorbent sweat patches are attached to various anatomical sites after the skin is thoroughly cleaned with deionized water and dried. Thereafter, bottles containing fluid (e.g., sports drink and/or plain water) identified with athletes' names are weighed before the given practice. Athletes are instructed to drink only from their personal bottles and not to spit any of the fluid out. They are also instructed to urinate in a container if needed during the practice so that this lost mass can be considered for sweat rate calculations. After the activity, sweat patches are removed and the body is towelled dry before post- practice body mass is recorded. Finally, bottles are re-weighed so the volume consumed during the training session or race can be calculated and considered for sweat rate calculations. This method is used to determine sweat rate, ad libitum fluid intake and percent change in body mass (i.e., fluid balance) and helps to identify those athletes with high sweat sodium losses who may need to pay attention to sodium replacement.

While this technique is widely used in land-based sports[19, 20], its use in swimming is limited because of the possibility of the pool water affecting sweat composition by saturating the sweat absorbent pad. However, to date, only one research group4 investigated fluid and electrolyte balance in well trained swimmers using the abovementioned technique during 105 min long training sessions in a pool with water temperature of 27.4 ˚C. Mean sweat volume was 548 ± 243 ml and a sweat rate of 310 ± 100 ml/h. Sweat Na+ was 43 ± 14 mmol/L and Cl- was 31 ± 9 mmol/L. Despite the relatively low sweat rate reported by the authors, it is possible to identify salt losses through swimmers' sweat even though sweat is not the main thermoregulatory pathway for these athletes.

A study assessing sweat rate, but not composition, of swimmers reported a range of 314 to 415 ml/h[21], which was similar to another study reporting a sweat rate of 480 ml/h during prolonged swimming[22]. Cade et al. reported higher sweat rates ranging from 1180 to 1620 ml/h during 2 hours of high intensity swim training, but as the focus of the study was on muscle damage, no further detail was provided regarding ambient and water temperature[23]. These studies report sweat rate as millilitre per hour and others have suggested that sweat rate should be expressed as ml/km to better translate into educational messages for swimmers since training sessions for such athletes are mostly based on distance to be swum rather than time[21].

Sweat rate and composition have been reported to be different in swimmers. Henkin et al[24] compared sweat rate and electrolyte concentration in swimmers, runners, and non-athletes during cycling in the heat (35 ˚C). Swimmers exhibited a lower sweat volume (900 ± 300 ml) than runners (1500 ± 200 ml), but similar to non-athletes (600 ± 200 ml). Swimmers sweat Na+ (65.4 ± 5.5 mmol/L) and Cl- (61.2 ± 8.1 mmol/L) content were higher than runners (Na+ = 45.2 ± 7.5; Cl- = 38.9 ± 8.3 mmol/L), but similar to non-athletes (Na+ = 67.3 ± 8.5; Cl- = 58.3 ± 9.6 mmol/L). These results suggest differential adaptations of sweat glands in swimmers when compared to runners, which agrees with an earlier study suggesting that swimmers may not develop the same level of heat acclimatization as their training sessions are conducted in an environment that does not allow sweat evaporation[25] or probably simply because of less heat stress. Even so, it is possible to speculate that swimmers exercising for longer than 1 h on land might need to pay attention to electrolyte losses due to their potential to lose more salts through sweating.

One recent study performed with adolescent swimmers reported that more than 75% (out of 46 participants) of the swimmers were hypohydrated before practice[15]. This data matches with reports from different sports modalities indicating that athletes are hypohydrated before starting training sessions[26,27]. Higham et al[16] found that 85% of the swimmers were hypohydrated before training sessions based on urine specific gravity (USG) analysis. Pre-hydration level is usually determined by urine osmolality, USG, or urine colour scale[28]. To prevent dehydration, coaches and athletes can perform these measurements bearing in mind that urine colour may not be an indicator of post practice hydration level as swimming can change urine osmolality regardless of the hydration status[15]. The effect of water pressure against the skin decreases superficial vascular transmural pressure (pressure inside the vessel minus the outside pressure), thus causing haemodilution during the initial phase of immersion[29, 30]. As immersion continues (> 1/2 h) a reflex renal diuresis occurs and haemoconcentration prevails.

Factors that increase the risk of hyperthermia and/or dehydration in swimmers

Hyperthermia and dehydration are more likely to occur in open water than in indoor swimmers. However, there are extrinsic factors that can increase the chance of hyperthermia and dehydration even in indoor swimmers. For instance, there are multiple factors that may predispose athletes to heat illnesses that are not discussed in the context of sports. In Table 1 we list a number of factors that are known to increase the risk of hyperthermia and dehydration in athletes. In addition, evidence suggests that prior bouts of illness or inflammation may increase the risk of exertional heat illness regardless of the age, acclimatization levels, or other risk factors[31,32]. It is worth noting that most evidences come from athletes of other sports or military personnel who are potentially exposed to similar exertional levels as swimmers. Therefore, future studies are needed to test the extent by which these factors can indeed be an issue in swimming.

Risk Factor	Etiology
>31˚C water temperature	reduced/negligible cooling via convection
Sunlight	increased radiant heat transfer
Overtraining/High competition frequency	causes hypohydration, reduced plasma volume & thermoregulatory capacity
Excessive alcohol consumption	metabolic stimulation and inhibition of vasomotor reflexes that normally facilitates heat dissipation
Recent viral/bacterial infection	excess proinflammatory and pyrogenic cytokines, reduced thermoregulatory function
Lower fluid and electrolyte consumption	reduced plasma volume

Acute/chronic NSAID use	impaired heat tolerance, increased intestinal permeability, potentially increased chance of endotoxemia

Table 1: Risk factors for hyperthermia and dehydration in swimmers

Previous bouts of infection/inflammation

Athletes exposed to high exercise training volumes and intensities may develop immunosuppression that may increase the risks of developing viral or bacterial infection[33-35]. For instance, swimmers with a lower pre-season salivary IgA were more likely to contract upper respiratory tract infection during a 7-month training period[36,37]. Infection and inflammation are, sometimes, accompanied by fever[38]. Fever from a pre-existing illness may increase the normal hyperthermic response to exercise[31]. Dehydration has been discussed as one mechanism involved in the increased risk of hyperthermia in athletes with a previous period of infection, as it compromises thermoregulatory control mechanisms and was found to be a risk factor in young male runners that suffered heat stroke following respiratory or GI illness[39]. Although more research is needed to establish the impact that a previous bout of inflammation and/or infection has on swimmers' thermoregulatory response, caution should be taken to avoid hyperthermia when returning from these conditions.

Use of Non-Steroidal Anti-Inflammatory Drugs (NSAIDS)

NSAIDs (e.g., naproxen and aspirin) are one of the most common prescription and over the counter medications used to treat shoulder injuries and muscle pain/discomfort in swimmers[40]. The use of NSAIDS has a high prevalence among athletes and limited awareness of potential side effects[41]. The effect of high environmental temperatures on NSAIDs toxicity has not been well appreciated despite early reports showing increased aspirin toxicity (measured as lethality) in rats passively exposed to 36 ° C versus a thermoneutral environment[42]. One possible mechanism for the increased risk of heat illness when hyperthermia, exercise, and the use of NSAIDs are superimposed is the potential for enhanced intestinal permeability as NSAIDs can increase intestinal permeability within 24h of ingestion[43] and hyperthermia can increase ischemia-reperfusion induced intestinal damage[44]. This combination may lead to endotoxemia and advance for systemic inflammatory response syndrome. Thus, swimmers taking NSAIDs might have increased risk of heat illnesses although further work is needed to determine the magnitude of risk.

Nutritional aspects

The use of alcohol is often intimately associated with sport. Although alcohol can provide a source of energy to the working muscle, the negative effects on metabolic, cardiovascular, thermoregulatory, and neuromuscular aspects that may hinder performance are well known[45]. An early report demonstrated moderate alcohol consumption among young swimmers ranging from rarely to 2.1 L of beer per week[46]. Alcohol enhances diuresis and may lead to dehydration[47]. The magnitude of diuresis experienced is thought to be dependent upon the amount of alcohol consumed, and its effects on hydration status will be influenced by the concentration of alcohol relative to water in ingested beverages[48-50].

Shirreffs and Maughan[48] investigated effects of several beverages with a low alcohol (0, 1, 2 and 4%) content (2.212 ± 153 ml) on the restoration of water and electrolyte balance immediately after exercise-induced dehydration. They concluded that there was no difference in the recovery of body water content from dehydration with a beverage of up to 2% alcohol, but that the 4% alcohol drink increased urine output compared with the alcohol-free drink. This is consistent with the results of a study demonstrating that an additional 100 ml of urine would be produced for each 10 g of alcohol ingested, though this estimate was based on data from only a single subject[49]. Another early study was able to show more convincingly that the diuretic response in rats was proportional to the concentration of alcohol in a fluid bolus delivered by gastric intubation[50]. Alcohol consumption is an independent risk factor for heat illnesses due to the metabolic stimulation and inhibition of vasomotor reflexes that normally facilitates heat dissipation[31].

The use of creatine as a nutritional supplement is common by athletes including swimmers. While primarily used for potential benefits in sports of short duration and high intensity, its use has been seen in longer duration activities as well. Older theory suggested that creatine supplementation, through increasing intramuscular creatine phosphate stores, could potentially cause dehydration via increased osmotic pull of water from the extracellular fluid into the intracellular compartment51. It was thought that this impairment of ability to shift fluid into the extracellular space could be detrimental to maintenance of plasma volume during periods of high sweat rates required for thermoregulation[51]. This theory has been abandoned, as existing data on the effects of creatine on hydration status indicate an increase in total body water, typically without concurrent shifts in compartmental distribution[52-54]. Data indicates acute increases in total body water and ICF within 3 days[55], with longer time periods (~28 days) yielding no differences in fluid distribution[54]. Studies show that creatine does not hinder thermoregulation[51, 56, 57], in either men or women[58], and during exercise in the heat[59], with some data supporting improvements in thermoregulatory measures including core temperature and heart rate[60, 61]. Current data supports the theory that by encouraging a hyperhydrated state via increased total body water, thermoregulatory mechanisms are not impaired, and may potentially be improved.

Caffeine consumption is pervasive in everyday food items and taken purposefully as a nutritional supplement. Caffeine is a known diuretic and has been previously thought to potentially exacerbate dehydration and/or electrolyte imbalance, which could contribute to impaired thermoregulation during exercise in the heat. However, current data indicates caffeine to lack negative effects on fluid and electrolyte balance[62-64], including during exercise in heat[65,66], in chronic consumers[67], and during post workout rehydration[68]. Use of caffeine is not detrimental, and may indeed be a useful adjunct to a comprehensive nutritional plan in long duration open water swimming events[69].

Overdrinking, hyponatremia, and drink temperature

Besides the aspects discussed above, many other aspects can have potential impact on swimming performance, but they still deserve more research. For instance, overdrinking can be as harmful as dehydration[71]. However, it is challenging to precisely monitor the volume of water intake in swimmers because they often involuntarily drink water from the pool/sea/river. One major concern related to overdrinking fluids with low electrolyte concentration is hyponatremia (low serum sodium concentration – below 135 mEq/L), which can impair brain function due to edema. The incidence of hyponatremia in swimmers is thought to be higher in females than in males open-water swimmers.

For instance, Wagner et al.[72] investigated the prevalence of exercise-associated hyponatremia in 25 male and 11 female open-water ultra-endurance swimmers participating in the 'Marathon-Swim' in Lake Zurich, Switzerland, covering 26.4 km. They found that two males (8%) and four females (36%) developed hyponatremia where one female was symptomatic with plasma sodium [Na+] of 127 mmol/L. Interestingly, monitored fluid intake was neither associated with changes in body mass, post-race plasma sodium or the change in plasma sodium, suggesting that swimmers drank water from other sources other than that provided by their staff. It is important to highlight that overdrinking is not the only cause of hyponatremia. Other factors such as inadequate secretion of suppression of antidiuretic hormone, which leads to excessive fluid retention and fail to mobilize osmotically inactive sodium from internal sources are potential factors involved in the development of hyponatremia[72].

Whether there is an optimal drink temperature to enhance performance in swimmers is another question that deserves attention. Hue et al.15 assessed the effects of ingesting drinks with different temperatures (cold = 1.1 ˚C or neutral = 28 ˚C) during open water swimming in a tropical environment. Cold-water ingestion significantly decreased core temperature. However, heart rate and performance were not affected by drink temperature. Although these results suggest that drink temperature do not affect overall performance, it may be a useful strategy to prevent hyperthermia in open water swimmers, mainly when competition takes place in hot weather.

Practical recommendations to avoid significant dehydration and heat stress in swimmers

The following recommendations aim to prevent significant dehydration and heat stress in swimmers considering the evidences reported in this review.

- Education about the importance of fluid ingestion to swimmers' performance is fundamental and should start in the early stages of their career.
- Track changes in body mass during training and races in different environmental conditions to determine individual sweating rates and hydration habits. This will help identify swimmers who are at risk of significant dehydration.
- Individualize the hydration strategy based on swimmers' sweating rate and drink preferences (e.g., beverage type and flavour to promote voluntary fluid intake).
- Swimmers should drink enough fluid during training/races to prevent >2% dehydration. One strategy to achieve this goal in swimmers is to encourage them to drink throughout a day of competition. Overdrinking relative to sweat losses should also be avoided.
- After exercise, if dehydration is severe (>5% of body mass) or rapid rehydration is needed (e.g., < 24 h before next practice or race) drink ~1.5 L of fluid for each 1 kg of body mass deficit70.
- Consuming a beverage with sodium or sodium-containing snacks

/ foods, helps replace sweat sodium losses, stimulate thirst and retain the ingested fluids.

- Caffeine and/or creatine use are unlikely to affect thermoregulatory mechanisms negatively.
- Avoid high intensity training sessions and/or competition when returning from periods of infection or prolonged NSAIDs use.
- Be aware that alcohol is likely to increase the risk of heat-related illnesses.

Conclusions

Swimmers and coaches often neglect hyperthermia and dehydration probably because swimming is a sport performed in an environment that favours heat loss and because sweat evaporation is not the main thermoregulatory pathway involved. Even so, evidences suggest that salt losses occur through swimmers' sweat despite a lower sweat rate compared to athletes from other land-based sports. Evidences also suggest that swimmers are likely to start practices and races already hypohydrated, which further enhances the danger of heat related illnesses and impairments in performance. Open water swimmers are, oftentimes, exposed to environments that increase the risk of hyperthermia and dehydration due to the duration of the races and the unpredictable weather conditions. We identified factors that may enhance the risk of hyperthermia and dehydration in swimmers such as the use of NSAIDs and use of alcohol. In addition, swimmers returning from periods of infection/inflammation must bear in mind the potential for compromised thermoregulatory function during training and races. Creatine supplementation and caffeine consumption are unlikely to compromise thermoregulatory response. In fact, the latter may be a useful adjunct to a comprehensive nutritional plan in long duration swimming events.

References

1. Mujika I, Chatard JC, Busso T, Geyssant A, Barale F, Lacoste L. Effects of training on performance in competitive swimming. Can J Appl Physiol. 1995;20(4):395-406.
2. Gonzalez-Alonso J, Quistorff B, Krustrup P, Bangsbo J, Saltin B. Heat production in human skeletal muscle at the onset of intense dynamic exercise. J Physiol. 2000;524 Pt 2:603-615.
3. Shibasaki M, Wilson TE, Crandall CG. Neural control and mechanisms of eccrine sweating during heat stress and exercise. J Appl Physiol (1985). 2006;100(5):1692-1701.
4. Maughan RJ, Dargavel LA, Hares R, Shirreffs SM. Water and salt bal-

ance of well-trained swimmers in training. Int J Sport Nutr Exerc Metab. 2009;19(6):598-606.
5. Nielsen B, Davies CT. Temperature regulation during exercise in water and air. Acta Physiol Scand. 1976;98(4):500-508.
6. Costill DL, Cahill PJ, Eddy D. Metabolic responses to submaximal exercise in three water temperatures. J Appl Physiol. 1967;22(4):628-632.
7. Bradford CD, Lucas SJ, Gerrard DF, Cotter JD. Swimming in warm water is ineffective in heat acclimation and is non-ergogenic for swimmers. Scand J Med Sci Sports. 2015;25 Suppl 1:277-286.
8. FINA. FINA Open Water Swimming Rules. 2015; http://www.fina.org/sites/default/files/finaowrules_20152017.pdf. Accessed 18th June 2016, 2016.
9. Otani H, Kaya M, Tamaki A, Watson P, Maughan RJ. Effects of solar radiation on endurance exercise capacity in a hot environment. Eur J Appl Physiol. 2016;116(4):769-779.
10. Croucher M. Death of US swimmer Fran Crippen was 'a disaster waiting to happen'. 2012; http://www.thenational.ae/news/uae-news/death-of-us-swimmer-fran-crippen-was-a-disaster-waiting-to-happen. Accessed June 18th, 2016.
11. Macaluso F, Barone R, Isaacs AW, Farina F, Morici G, Di Felice V. Heat stroke risk for open-water swimmers during long-distance events. Wilderness Environ Med. 2013;24(4):362-365.
12. Harris KM, Henry JT, Rohman E, Haas TS, Maron BJ. Sudden death during the triathlon. JAMA. 2010;303(13):1255-1257.
13. Eichner ER. The mystery of swimming deaths in athletes. Curr Sports Med Rep. 2011;10(1):3-4.
14. Asplund CA, Creswell LL. Hypothesised mechanisms of swimming-related death: a systematic review. Br J Sports Med. 2016.
15. Hue O, Monjo R, Riera F. Imposed Cold-water Ingestion during Open Water Swimming in Internationally Ranked Swimmers. Int J Sports Med. 2015; 36 (11), 941-946.
16. Higham DG, Naughton GA, Burt LA, Shi X. Comparison of fluid balance between competitive swimmers and less active adolescents. Int J Sport Nutr Exerc Metab. 2009;19(3):259-274.
17. Wendt D, van Loon LJ, Lichtenbelt WD. Thermoregulation during exercise in the heat: strategies for maintaining health and performance. Sports Med. 2007;37(8):669-682.
18. Sawka MN, Noakes TD. Does dehydration impair exercise performance? Med Sci Sports Exerc. 2007;39(8):1209-1217.
19. Shirreffs SM, Aragon-Vargas LF, Chamorro M, Maughan RJ, Serratosa L, Zachwieja JJ. The sweating response of elite professional soccer players to training in the heat. Int J Sports Med. 2005;26(2):90-95.
20. Maughan RJ, Shirreffs SM, Merson SJ, Horswill CA. Fluid and electrolyte balance in elite male football (soccer) players training in a cool environment. J Sports Sci. 2005;23(1):73-79.
21. Cox GR, Broad EM, Riley MD, Burke LM. Body mass changes and voluntary fluid intakes of elite level water polo players and swimmers. J Sci Med Sport. 2002;5(3):183-193.
22. Lemon PW, Deutsch DT, Payne WR. Urea production during prolonged

swimming. J Sports Sci. 1989;7(3):241-246.
23. Cade JR, Reese RH, Privette RM, Hommen NM, Rogers JL, Fregly MJ. Dietary intervention and training in swimmers. Eur J Appl Physiol Occup Physiol. 1991;63(3-4):210-215.
24. Henkin SD, Sehl PL, Meyer F. Sweat rate and electrolyte concentration in swimmers, runners, and nonathletes. Int J Sports Physiol Perform. 2010;5(3):359-366.
25. McMurray RG, Horvath SM. Thermoregulation in swimmers and runners. J Appl Physiol Respir Environ Exerc Physiol. 1979;46(6):1086-1092.
26. Logan-Sprenger HM, Palmer MS, Spriet LL. Estimated fluid and sodium balance and drink preferences in elite male junior players during an ice hockey game. Appl Physiol Nutr Metab. 2011;36(1):145-152.
27. Osterberg KL, Horswill CA, Baker LB. Pregame urine specific gravity and fluid intake by National Basketball Association players during competition. J Athl Train. 2009;44(1):53-57.
28. Armstrong LE, Pumerantz AC, Fiala KA, et al. Human hydration indices: acute and longitudinal reference values. Int J Sport Nutr Exerc Metab. 2010;20(2):145-153.
29. Khosla SS, DuBois AB. Fluid shifts during initial phase of immersion diuresis in man. J Appl Physiol Respir Environ Exerc Physiol. 1979;46(4):703-708.
30. Epstein M. Renal effects of head-out water immersion in man: implications for an understanding of volume homeostasis. Physiol Rev. 1978;58(3):529-581.
31. Leon LR, Bouchama A. Heat stroke. Compr Physiol. 2015;5(2):611-647.
32. Gardner JW, Kark JA, Karnei K, et al. Risk factors predicting exertional heat illness in male Marine Corps recruits. Med Sci Sports Exerc. 1996;28(8):939-944.
33. Atamaniuk J, Vidotto C, Tschan H, Bachl N, Stuhlmeier KM, Muller MM. Increased concentrations of cell-free plasma DNA after exhaustive exercise. Clin Chem. 2004;50(9):1668-1670.
34. Brahmi Z, Thomas JE, Park M, Park M, Dowdeswell IR. The effect of acute exercise on natural killer-cell activity of trained and sedentary human subjects. J Clin Immunol. 1985;5(5):321-328.
35. Edwards AJ, Bacon TH, Elms CA, Verardi R, Felder M, Knight SC. Changes in the populations of lymphoid cells in human peripheral blood following physical exercise. Clin Exp Immunol. 1984;58(2):420-427.
36. Pyne DB, Gleeson M. Effects of intensive exercise training on immunity in athletes. Int J Sports Med. 1998;19 Suppl 3:S183-191; discussion S191-184.
37. Gleeson M, Hall ST, McDonald WA, Flanagan AJ, Clancy RL. Salivary IgA subclasses and infection risk in elite swimmers. Immunol Cell Biol. 1999;77(4):351-355.
38. Kluger MJ, Kozak W, Conn CA, Leon LR, Soszynski D. Role of fever in disease. Ann N Y Acad Sci. 1998;856:224-233.
39. Richards R, Richards D, Whittaker R. Method of predicting the number of casualties in the Sydney City-to-Surf fun runs. Med J Aust. 1984;141(12-13):805-808.
40. Alaranta A, Alaranta H, Helenius I. Use of prescription drugs in athletes. Sports Med. 2008;38(6):449-463.

41. Gorski T, Cadore EL, Pinto SS, et al. Use of NSAIDs in triathletes: prevalence, level of awareness and reasons for use. Br J Sports Med. 2011;45(2):85-90.
42. Gordon CJ. Temperature Regulation in Laboratory Rodents: Cambridge University Press; 1993.
43. Bjarnason I, Takeuchi K. Intestinal permeability in the pathogenesis of NSAID-induced enteropathy. J Gastroenterol. 2009;44 Suppl 19:23-29.
44. Oliver SR, Phillips NA, Novosad VL, Bakos MP, Talbert EE, Clanton TL. Hyperthermia induces injury to the intestinal mucosa in the mouse: evidence for an oxidative stress mechanism. Am J Physiol Regul Integr Comp Physiol. 2012;302(7):R845-853.
45. Flores-Salamanca R, Aragon-Vargas LF. Postexercise rehydration with beer impairs fluid retention, reaction time, and balance. Appl Physiol Nutr Metab. 2014;39(10):1175-1181.
46. Smith MP, Mendez J, Druckenmiller M, Kris-Etherton PM. Exercise intensity, dietary intake, and high-density lipoprotein cholesterol in young female competitive swimmers. Am J Clin Nutr. 1982;36(2):251-255.
47. Hobson RM, Maughan RJ. Hydration status and the diuretic action of a small dose of alcohol. Alcohol Alcohol. 2010;45(4):366-373.
48. Shirreffs SM, Maughan RJ. Restoration of fluid balance after exercise-induced dehydration: effects of alcohol consumption. J Appl Physiol (1985). 1997;83(4):1152-1158.
49. Eggleton MG. The diuretic action of alcohol in man. J Physiol. 1942;101(2):172-191.
50. Crow LT. Diencephalic Influence in Alcohol Diuresis. Physiol Behav. 1968;3(2):319-&.
51. Lopez RM, Casa DJ, McDermott BP, Ganio MS, Armstrong LE, Maresh CM. Does creatine supplementation hinder exercise heat tolerance or hydration status? A systematic review with meta-analyses. J Athl Train. 2009;44(2):215-223.
52. Sobolewski EJ, Thompson BJ, Smith AE, Ryan ED. The Physiological Effects of Creatine Supplementation on Hydration: A Review. American Journal of Lifestyle Medicine. 2011;5(4):320-327.
53. Dalbo VJ, Roberts MD, Stout JR, Kerksick CM. Putting to rest the myth of creatine supplementation leading to muscle cramps and dehydration. Br J Sports Med. 2008;42(7):567-573.
54. Powers ME, Arnold BL, Weltman AL, et al. Creatine Supplementation Increases Total Body Water Without Altering Fluid Distribution. J Athl Train. 2003;38(1):44-50.
55. Ziegenfuss TN, Lowery LM, Lemon PWR. Acute Fluid Volume Changes in Men During Three Days of Creatine Supplementation. Journal of Exercise Physiology Online. 1998;1(3).
56. Mendel RW, Blegen M, Cheatham C, Antonio J, Ziegenfuss T. Effects of creatine on thermoregulatory responses while exercising in the heat. Nutrition. 2005;21(3):301-307.
57. Weiss BA, Powers ME. Creatine supplementation does not impair the thermoregulatory response during a bout of exercise in the heat. J Sports Med Phys Fitness. 2006;46(4):555-563.
58. Rosene JM, Whitman SA, Fogarty TD. A Comparison of Thermoregulation

With Creatine Supplementation Between the Sexes in a Thermoneutral Environment. J Athl Train. 2004;39(1):50-55.
59. Watson G, Casa DJ, Fiala KA, et al. Creatine use and exercise heat tolerance in dehydrated men. J Athl Train. 2006;41(1):18-29.
60. Kern M, Podewils LJ, Vukovich M, Buono MJ. Physiological Response to Exercise in the Heat Following Creatine Supplementation. Journal of Exercise Physiology Online. 2001;4(2):18-27.
61. Kilduff LP, Georgiades E, James N, et al. The effects of creatine supplementation on cardiovascular, metabolic, and thermoregulatory responses during exercise in the heat in endurance-trained humans. Int J Sport Nutr Exerc Metab. 2004;14(4):443-460.
62. Armstrong LE. Caffeine, body fluid-electrolyte balance, and exercise performance. Int J Sport Nutr Exerc Metab. 2002;12(2):189-206.
63. Armstrong LE, Casa DJ, Maresh CM, Ganio MS. Caffeine, fluid-electrolyte balance, temperature regulation, and exercise-heat tolerance. Exerc Sport Sci Rev. 2007;35(3):135-140.
64. Falk B, Burstein R, Rosenblum J, Shapiro Y, Zylber-Katz E, Bashan N. Effects of caffeine ingestion on body fluid balance and thermoregulation during exercise. Can J Physiol Pharmacol. 1990;68(7):889-892.
65. Del Coso J, Estevez E, Mora-Rodriguez R. Caffeine effects on short-term performance during prolonged exercise in the heat. Med Sci Sports Exerc. 2008;40(4):744-751.
66. Del Coso J, Estevez E, Mora-Rodriguez R. Caffeine during exercise in the heat: thermoregulation and fluid-electrolyte balance. Med Sci Sports Exerc. 2009;41(1):164-173.
67. Roti MW, Casa DJ, Pumerantz AC, et al. Thermoregulatory responses to exercise in the heat: chronic caffeine intake has no effect. Aviat Space Environ Med. 2006;77(2):124-129.
68. Dias JC, Roti MW, Pumerantz AC, et al. Rehydration after exercise dehydration in heat: Effects of caffeine intake. J Sport Rehabil. 2005;14(4):294-300.
69. Shaw G, Koivisto A, Gerrard D, Burke LM. Nutrition considerations for open-water swimming. Int J Sport Nutr Exerc Metab. 2014;24(4):373-381.
70. Shirreffs SM, Sawka MN. Fluid and electrolyte needs for training, competition, and recovery. J Sports Sci. 2011; 29 Suppl 1:S39-46
71. Beltrami FG, Hew-Butler T, Noakes TD. Drinking policies and exercise-associated hyponatraemia: is anyone still promoting overdrinking? Br J Sports Med. 2008; 42(10):796-501. Review. Erratum in: Br J Sports Med. 2009; 43(4):310-1.
72. Wagner S, Knechtle B, Knechtle P, Rüst CA, Rosemann T. Higher prevalence of exercise-associated hyponatremia in female than in male open-water ultra-endurance swimmers: the 'Marathon-Swim' in Lake Zurich. Eur J Appl Physiol. 2012; 112(3):1095-106.
73. Noakes TD, Sharwood K, Speedy D, Hew T, Reid S, Dugas J, Almond C, Wharam P, Weschler L. Three independent biological mechanisms cause exercise-associated hyponatremia: evidence from 2,135 weighed competitive athletic performances. Proc Natl Acad Sci USA. 2005; 102:18550–55.

Biomechanics of relay swimming starts: state of the art

K. de Jesus[1,2,3], K. de Jesus[1,2,3], L. Mourão [1,2,4], L. S. Coelho[5,6], L. Machado[1,2], R.J. Fernandes[1,2], J.P. Vilas-Boas[1,2]

Introduction

In competitive swimming, starting techniques performed in competitive events differ according to the received starting signal, with the auditory and visual stimulus being used for individual and first swimmer of relays, and for the second, third and fourth changeovers, respectively ([1]; Figure 1). In fact, the first swimmer should be stationary until the starting signal is given (FINA SW 4.1 and 4.2 rules) and the second, third and fourth swimmers should be in contact with the platform when their incoming teammate touches the starting wall (FINA SW 2.6.5 rule) but can move him/herself to leave the block in a more explosive way. Starts performed in individual ventral and dorsal events have been extensively studied in comparison to the relay starting techniques, probably due to the greater number of official individual events [2] and the higher complexity that relay experimental research protocols require (with two swimmers simultaneously performing different tasks; [3]).

1. Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Portugal;
2. Porto Biomechanics Laboratory, University of Porto, Porto, Portugal;
3. Faculty of Physical Education and Physiotherapy, Federal University of Amazonas, Amazonas, Manaus, Brazil;
4. Superior School of Industrial Studies and Management, Porto Polytechnic Institute, Vila do Conde, Portugal;
5. Industrial and Systems Engineering Graduate Program, Pontifical Catholic University of Paraná, Brazil
6. Electrical Engineering Graduate Program, Federal University of Paraná, Brazil

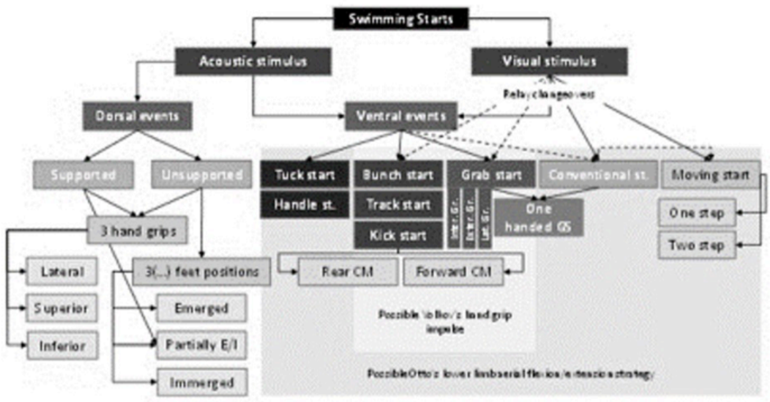


Figure 1. Official swimming starting conditions and technical solutions most commonly used (adapted from Vilas-Boas and Fernandes [1]).

Saavedra et al. [4] have pointed out that, from a range of 19 international competitions held between 2000 to 2012, high proficient starters achieved better performances in international swimming events (specially in 4x100 m race), evidencing the need for deeper research on the topic. Moreover, although three out of 17 events in the Olympic swimming programme are relays, coaches remain allocating only a small-time percentage for the specific training of the relay starts prior to national and international events [2]. Furthermore, since 2013, new relay races with mixed gender teams have been added to World Championship events (FINA SW 10.10 rule)

On the relay swimming events, FINA authorizes the second, third and fourth swimmers to begin their starting motion before the incoming swimmer has touched the wall ([5]), just requiring that one foot is in contact with the starting block at the time the former swimmer finishes his/her course (the relay exchange timing tolerance is -0.03 s; [4]). To reduce the potential for a false start, leading to an automatic disqualification, some swimmers prefer to use the conventional non-step start technique, involving a circular backswing upper limb movement [2,3,6]. Here, the risk of going out before the colleague touches the wall is much lower, but the impulse of the upper limbs is increased comparing to the grab start [7]. In the past two decades, new step starting techniques with one or two steps approach before driving off the platform (Figure 2) have been observed during international competitions and later examined from a scientific point of view [3,6]. Findings indicated that the step starting involves longer exchange block times than non-step techniques [6] and the effective use of the double-step motion depends on the swimmer's ability to take longer steps [3].

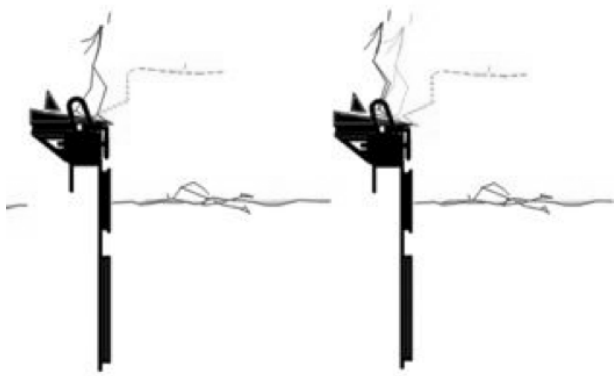


Figure 2. Relay start techniques: One and two steps (left and right panels, respectively).

The importance of the swimming starts for enabling better performance on relay events evidences the need to synthesise the scientific knowledge regarding biomechanical behaviour of relay start techniques. Literature review is available regarding ventral [8] and dorsal (backstroke events) start techniques [9], but no survey has been conducted for a comprehensive knowledge of the relay start techniques literature. The aim of this chapter is to review and discuss the state of the art regarding relay start biomechanics, using peer-reviewed journal articles and relevant congresses and symposium series (as the Biomechanics and Medicine in Swimming Symposiums and the International Society of Biomechanics in Sports Conferences).

Development

Search strategy

The literature search was performed using PubMed and Scopus electronic databases, and only for English written documents published before March 2017. The reference lists of the articles were also used to ensure, as far as practically possible, that all appropriate studies were considered for inclusion. In addition, it was also analysed the Proceedings of the Biomechanics and Medicine in Swimming (BMS) Symposiums and of the International Society of Biomechanics in Sports (ISBS) Congresses from 1980 to 2016. Key words including “swimming”, “relay” and “start” were used to locate documents.

Inclusion and exclusion criteria

Included studies were experimental biomechanical approaches with able-bodied swimmers. Documents available only as abstracts and duplicated studies from original investigations were excluded.

Results and Discussion

Fifteen studies were obtained from the preliminary search, but only six studies have met the inclusion criteria, being one from a swimming specific journal, four from peer-review journals and another from the Proceedings book of the BMS conference (Table 1).

Author (s)	Main aim	Sample	Setting
Gambrel et al. [18]	To identify the mechanical characteristics of the step start and to compare it with a conventional relay start	Seven college male swimmers	Experimental
McLean et al. [3]	To compare the three step starts (with a full step length) and the non-step start. To evaluate the restriction of step length on performance	Ten collegiate male swimmers	Experimental
Takeda et al. [6]	To evaluate the effectiveness of the no-step, single-step and double-step start techniques to determine the relay start performance	Eight well-trained male college swimmers	Experimental
Saavedra et al. [4]	To analyse the association between relay exchange block time and final performance in relay events in international championships	827 relay race records from Olympic, World, European, Commonwealth and Pan Pacific Games swimmers	Competition
Skorski et al. [5]	To investigate if swimming performance is better in a relay race than in the corresponding individual race.	166 elite male swimmers	Competition
Fischer et al. [2]	To compare the offensive (minimizing change-over time) and conservative (maximizing horizontal peak force) strategies using the non-step start technique	Twelve male and twelve female national level swimmers	Experimental

Table 1. Descriptive analysis of the six included studies regarding swimming starting relays, displaying the authors, main goal, swimmers' sample proficiency and data collection setting.

Table 1 reveals that three experimental studies analysed the effects of non-step and step swimming starting techniques [3,6,13], and another compared two intervention strategies considered feasible to be implemented one week ahead of competition [2]. Comparisons between non-step and step starts have revealed different results for performance, however McLean et al. [3] and Takeda's et al. [6] findings have corroborated about the importance of proper step length. Fischer et al. [2] noticed that while minimizing changeover time may eventually enforce the risk of a false start, keeping it within a safe range may prevent the relay team from disqualification. Researchers have also focused at the influence of the changeover time on the final relay race performance at high calibre swimming events as a function of sex and classification (medallists, first to third, and non-medallists, fourth to eight) and at the confirmation if starting at relay events provide better performance than individual ones ([4,5]; respectively). Despite being a small amount of studies performed in relay techniques, they have raised and answered relevant coach questions before selecting a start position that can result in better performance [10].

The studies conducted in the laboratory setting adopted a small number of swimmers, which undermines the effect size and results reproducibility [11]. However, ~ 10 swimmers have been considered a common sample size number in swimming start studies due to the availability for familiarization and testing protocols using complex data collection methodology. From the four studies using the experimental setting, three implemented a relay start techniques familiarisation and one refused this period to analyse the effects of the feet position usage.

A small variation in experimental design has been noticed, being four studies conducted in experimental and two in competition setting. It has been observed a considerable number of sophisticated and useful solutions for relay swimming start analysis (i.e. video cameras and force plates). However, these methods must cover the scientific demands of validity, reliability and accuracy along with the more practical issues like range of usage, complexity and costs [12]

The data collection setting determines the biomechanical variables possible to be assessed and their study relevance. Data collected in the experimental setting are more accurate and reliable, but the validity can be substantially restricted. The opposite is observed in the field, since variables can be defined with high validity, but restricted accuracy and reliability [12] Two biomechanical branches were predominantly used for data recordings, kinematics (video camera images) and kinetics (force-plates). The pioneer study considering relay start techniques used a high-speed cinematography camera (LoCAm, model 51, 16 mm) to assess block, flight and 10 m time, horizontal and vertical centre of mass position, centre of mass take-off angle, height and velocity and vertical centre of mass position at water entry [13]. The effectiveness of dive starts has been measured by the time to a set distance, ranging from 1.52 to 25 m (cf. [14]). The start performance is commonly measured between the start signal and the moment when the swimmer's head reaches the 15th meter [15]. The 10, 7.5 and 5 m mark has been pointed out as appropriate to assess start performance because the effects of other swim variables are avoided, being only the block, flight, entry and glide time included in most of these distances (e.g. [3]). The choice of performance measure might affect the conclusions drawn from a technique analysis [16], thus researchers should define a common variable to quantity performance in relay starts.

The changeover time measured at experimental and competition setting (i.e. from the incoming swimmer wall contact and the outgoing swimmer's toe-off; [4,5]) has been considered the most important variable for shorter 15 m start time [4]. The perfect exchange time is achieved when the toes of the outgoing swimmer leave the starting platform while the incoming swimmer touches the wall [5]. Researches on relay starts, so far, have implicitly assumed that minimizing the changeover time would be the best strategy for a relay start prior to the race [2]. These authors evidenced that improvements in the relay start time (i.e. between the wall contact of the incoming swimmer and the head passage of the relay starter at 7.5 m) are, for the most part, related to decreases in the changeover time. In addition, they found that feedback on the horizontal peak force provided superior effects on the reaction start time when compared with changeover information. For them, independent of the start technique, differences in the attentional focus (i.e. changeover time or horizontal peak force) during the relay start may influence relay start time.

Temporal data has been presented as the most common variables measured in relay start techniques, however, following Gambrel and co-authors [13] the most recent studies have used deterministic factors identified from an individual swimming start model [18] from the take-off until swimmers' immersion. Authors have adopted distinct methodological procedures to assess the take-off angle and horizontal velocity using cinematographic, digital video cameras and ground reaction force measurements [13, 2,6]. In addition, McLean et al. [3] and Takeda et al. [6] assessed the vertical velocity, and ground reaction forces, respectively, which allows an overall understanding about the swimmers' locomotion over the block and three-dimensional forces generated before the take-off instant. The variables measured during swimmer block contact as the take-off angle, velocities and external forces are considered flight time influencers [17]. In fact, if a limb is in contact to a force platform, the respective three-dimensional force and momentum should be measured to maximise training efficiency [18].

The effects of the step start were firstly assessed by Gambrel et al. [13] who verified no differences when compared to the conventional no-step start. Despite these findings, authors pointed out that the flight distance and time to 10 m could be covered longer and faster using the step start. McLean and co-authors [3] also found that time to 10 m was not shorter when compared step and no-step start, although some mechanical advantages were observed. The double and single step start increased horizontal take-off velocity and take-off height, respectively, and the double, single step apart and single step together increased the take-off vertical velocity. Authors included the analysis of restricting step length by 50% and noticed little effect on step starts with exception of horizontal and vertical take-off velocity, reduced and increased, respectively. Data suggested that step starts offered performance improvements, but those were not widespread and were dependent on the ability to take longer steps.

Contrarily to McLean et al. [3], further comparison between non-step, single-step and double step start revealed similar horizontal take-off velocity, although relay time (i.e. from the swimmer's contact until the take-off) decreased in the order no-step, single and double-step start [6], suggesting the former as better for relay starts performance. According to these authors the familiarisation period might not have been enough since swimmers have incorrectly performed the foot placement during step starts.

The most recent relay starts studies formulated three different research questions to characterise available relay start techniques. Saavedra and co-authors [4] analysing the association between relay exchange block time and swimming final performance found that the former was especially relevant for women's relay medallists in the 4x100 freestyle and medley. Authors considered that the exchange block time should be considered as one of the relay starts performance variables, being needed to be included as part of training. In opposition to Saavedra et al. [4], horizontal peak force, as a conservative relay strategy, showed a clear advantage over the changeover time strategy to reduce relay time [2].

Skorski et al. [5] studied the individual swimming performance related to the corresponding individual race and verified that during relays, highly trained swimmers competing in 1st position did not show any different compared with their corresponding individual performance. However, swimmers competing in second to fourth relay team position demonstrated faster times in the 100 m and first half of the 200 m relays than in their individual events, which was nullified when finishing times were adjusted for the flying start.

Future suggestions

The presented studies evidenced important results for biomechanics, coaches and swimmers, but further research questions should be raised. Firstly, researchers should consider the effects of the current starting block configuration on biomechanical variables when swimmers perform the step starts. Secondly, an electromyographical approach should be implemented for better understanding about the muscular activation sequence and intensity. Thirdly, linear and non-linear mathematical methods should be built using traditional biomechanical variables to model and predict relay start performance.

Conclusions

This chapter have exhibited the research background in relay start techniques, summing up six included studies following the inclusion criteria. Biomechanics, coaches and swimmers have been provided with some objective evidence about kinematics and kinetics data of four relay start techniques, no-step, one-step apart, one-step together and two-step. Further methodological advances can be made for an extensive comprehension of biomechanics during relay start techniques considering the back plate and respective effects, the electromyographic analysis and mathematical prediction models.

Acknowledgments

Coordination for the Improvement of Higher Education Personnel and Foundation for Science and Technology 039-2014 (grant number 99999.008578/2014-01)

References

1. Vilas-Boas, J.P., Fernandes, R.J. (2003). Swimming starts and turns: determinant factors of swimming performance. Actes des 3èmes journées spécialisées de natation. Université Lille, pp. 84–95
2. Fisher, S., Braun, C., Kibele, A. (2017). Learning relay start strategies in swimming: what feedback is best? European Journal of Sport Science, 17(3), 257-263.
3. McLean, S.P., Holthe, M.J., Vint, P.F., Beckett, K.D., Hinrichs, R.N. (2010). Additional of an approach to a swimming relay start. Journal of Applied Biomechanics, 16, 342-355.
4. Saavedra, J.M., García-Hermoso, A., Escalante, Y., Domingues, A.M., Arellano, R., Navarro, F. (2014). Relationships between exchange block time in swim starts and final performance in relay races in international championships. Journal of Sports Sciences, 32(19), 1783-1789.
5. Skorski, S., Etxebarria, N., Thompson, K.G. (2016). Breaking the myth that relay swimming is faster than individual swimming. International Journal of Sports Physiology and Performance, 11, 410-413.
6. Takeda, T., Takagi, H., Tsubakimoto, S. (2010). Comparison among three relay starts in competitive swimming. In: P-L Kjendlie, R. K. Stallman, J. Cabri (eds), XIth International Symposium on Biomechanics and Medicine in Swimming, pp. 170-172.
7. Ayalon, A., Van Gheluwe, B., Kanitz, M. (1975). A comparison of four styles of racing starts in swimming. In. L. Lewillie and J.P. Clarys (Eds.). Swimming II (pp 233-240). Baltimore University Park Press.
8. Vantorre, J., Chollet, D., Seifert, L. (2014). Biomechanical analysis of the swim-start: a review. Journal of Sports Science and Medicine, 13, 223-231.
9. De Jesus, K., de Jesus, K., Fernandes, R.J., Vilas-Boas, J.P., Sanders, R. (2014). The backstroke swimming start: state of the art. Journal of Human Kinetics, 10(42), 27-40.
10. Seifert, L., Vantorre, J., Lemaitre, F., Chollet, D., Toussaint, H.M., Vilas-Boas, J.P. (2010). Different profiels of the aerial start phase in fornt crawl. Journal of Strength and Conditioning Research, 24(2), 507-516.
11. Button, K. S., Ioannidis, J.P.A., Mokrysz, C., Nosek, B.A., Flint, J., Robinson, E.S. (2013). Power failure: why small sample undermines the reliability of neuroscience. Nature reviews. Neuroscience, 14, 365, 376.
12. Schwameder, H. (2008). Aspects and challenges of applied sport biomechanics research. In: Y-H. Kwon, J. Shim, J.K. Shim, I-S. Shin (eds.), XXVI International Symposium on Biomechanics in Sports. Seoul National University, pp 25-28.
13. Gambrel, D.W., Blanke, D., Mellion, M.B. (1991). A biomechanical comparison of two relay starts in swimming. Journal of Swimming Research, 2, 5-9.
14. Galbraith, H., Scurr, J., Hencken, C., Wood, L., Graham-Smith, P. (2008). Biomechanical comparison of the track start and the modified one-handed track start in competitive swimming: an intervention study. Journal of Applied Biomechanics, 24, 307-315.
15. Elipot, M., Dietrich, G., Hellard, P., Houel, N. (2010). High level swimmers' kinetic effciency during the underwater phase of a grab start. Journal of

Applied Biomechanics, 26, 501-507.
16. Bezodis, N.E., Salo, A.I., Trewartha, G. Choice of Sprint start performance measure affects the performance-based ranking withing a group of sprinters: which is the most appropriate measure? Sports Biomechanics, 9(4), 258-269.
17. Guimarães, A.C.S., Hay, J.G. (1985). A mechanical analysis of the grab starting technique in swimming. International Journal of Sport Biomechanics, 1, 25-35.
18. Mourão, L., de Jesus, K., Viriato, N., Fernandes, R.J., Vilas-Boas, J.P., Vaz, M.A.P. (2016). Design and construction of a 3D force plate prototype for developing an instrumented swimming start block. Journal of Biomedical Engineering and Informatics, 2(2), 17-22.

Competition analysis in swimming: inter- and intra-individual variability of speed and stroking parameters management

David Simbaña-Escobar[1,2], **Philippe Hellard**[1,3], **Marta Avalos**[4,5], **Ludovic Seifert**[2]

Introduction

To achieve performance goals in competitive swimming there is a need to strike a delicate balance between movement pattern stability and variability because, although swimmers need to achieve consistent outcomes, they also need to be able to successfully adapt their movements to changes in the performance environment (Seifert, Komar, Barbosa, Toussaint, Millet, et al., 2014a). To achieve these aims, the ecological dynamics framework advocates that there is an intertwined relationship between the specific intentions, perceptions and actions of individual athletes which constrains this relationship between movement pattern stability and variability in each individual performer (Seifert & Davids, 2012). This inter-twined relation between an individual's intentions, perception and action processes needs to be carefully understood because of the insights it provides on expert performance in swimming.

Traditionally, a high-level of expertise in sport has been associated with the capacity to be able to reproduce a specific movement pattern consistently and to reduce attention demands during performance by increasing the automaticity of movement (Schmidt & Lee, 2011). It was assumed that the central nervous system functioned as an executive organizer and prescriber of motor programs and action plans charged with the task of producing stable movement patterns from an individual's effector system (Schmidt & Lee, 2011; Summers & Anson, 2009). From that

1. Research Department, French Federation of Swimming, Pantin, France
2. Centre d'Etudes des Transformations des Activités Physiques et Sportives, EA-3832, Faculty of Sport Sciences, University of Rouen Normandy, Rouen, France
3. Institut de Recherche Biomédicale et d'Epidémiologie du Sport, National Institute of Sport, Expertise and Performance (INSEP), Paris, France
4. INRIA SISTM, Team, F-33405 Talence, France
5. University of Bordeaux, INSERM, Bordeaux Population Health Research Center UMR 1219, F-33000, Bordeaux, France

viewpoint, expertise in sport was associated with a reduction in deviations in task performance from an ideal standard or movement template, which was represented in the central nervous system. By harnessing integrated feedback systems, swimmers were considered to modify the motor program entry parameters until expert behaviour was eventually achieved after many hours of practice (Schmidt & Lee, 2011). Traditionally, therefore, movement variability was considered as noise in performance and learning which should be minimized or eradicated to enable the production of highly functional movement programs (i.e. an artefact limiting an individual system's processing of information from input to output)(Davids, Bennett, & Newell, 2006; Newell & Corcos, 1993).

However, research in ecological dynamics has shown that movement system variability should not necessarily be construed as noise, detrimental to performance (Davids et al., 2006). Nor should it always be viewed as error, or a deviation from a putative expert model, which should be constantly corrected in swimmers. Inspired by Bernstein's work research program (Bernstein, 1996), movement system variability instead is now considered to exemplify the functional flexibility of a skilled athlete to respond to changes in dynamic performance constraints (Seifert, Button, & Davids, 2013; Seifert, Komar, Barbosa, Toussaint, Millet, et al., 2014a). A key idea is that movement pattern variability can be viewed as a functional property of skilled swimmers to help them adapt their movement behaviours to changing task and environmental constraints (such as glide, swimming speed, effect of start, turn, finish, fatigue (Hellard et al., 2008; Seifert, Komar, Barbosa, Toussaint, Millet, et al., 2014a; Seifert, Komar, Araújo, & Davids, 2016; Seifert, Komar, Crettenand, & Millet, 2014b). Given these theoretical advances in understanding behavioural variability, research within the ecological dynamics framework have argued that there is no ideal behavioural and race management solution that all swimmers should aspire during training and competition. Rather, functional behaviour emerged during training and race from the interaction of constraints on each individual swimmer (task, environmental and organismic; Newell, 1986); leading to intra-individual and inter-individual swimming speed variability as consistent performance outcomes are achieved. For instance, in 400-m international swimming competition, Mytton, Archer, Turner, Skorski, Renfree, Thompson, and St Clair Gibson, (2015a) emphasized that the variance of speed profiles tended to increase as the race progressed. Similar results were also observed by Robertson, Pyne, Hopkins, and Anson, (2009) when analysing between-swimmers average and standard deviation times for the 200-m freestyle for males and the 400-m freestyle for both gender. Mytton, Archer, St Clair Gibson and Thompson, (2014), Mytton, Archer, Turner, Skorski, Renfree, Thompson, and St Clair Gibson, (2015a) related this higher variance of swimming speed in the final lap to an indication of fatigue and deterioration in mechanical efficiency as the race progresses. In addition, Mytton et al., (2014) recently showed that performance in the final lap in 400-m (collected in international competitions between 2005 and 2011), and especially the differences in absolute, normalized, and relative speed can differentiate between medallists and non-medallists. These authors suggested that the success associated with a more pronounced end spurt could mean that medallists were able to call on reserves of energy not available to non-medallists three-quarters of the way through the race. These studies as well as other recent research on speed management in cyclic activities (e.g., running, swimming, cycling, skating, kayaking, etc) showed that pacing is a key element of performance and more importantly of winning the race (Foster et al., 1993, 2003, 2004, 2009; Thompson, Haljand, & MacLaren, 2000; Thompson, MacLaren, Lees, & Atkinson, 2004; Tucker & Lambert, 2006). However, these researches only consider lap times (i.e. average value of speed for 50-m lap) and even 100 m times for the 400-m freestyle event analysed by Mytton et al., (2014), Mytton, Archer, Turner, Skorski, Renfree, Thompson, & St Clair Gibson, (2015b) and Thompson et al. (2015), neglecting the possible effect of turning in the pacing. The main limitations of these studies might be the impossibility to accurately determine the inter-individual variability of race management.

Our study attempted to overcome this limitation by considering cycle-to-cycle variability to draw individual profile because recently, the functional role of behavioural variability has been supported by neuroscientific research highlighting the property of neurobiological system degeneracy. Degeneracy as nothing to do this the degradation of a system but could be defined by several authors from cognitive anatomy and theoretical neurobiology (Edelman & Gally, 2001; Price & Friston, 2002; Tononi, Sporns, & Edelman, 1999) as the capacity of system components that differ in structure to achieve the same function or performance output. This structural property in humans indicates the availability of an abundance of motor system degrees of freedom, which can take on different roles when assembling functional actions during sport performance. Research in ecological dynamics has demonstrated that degeneracy in complex perception-action systems provides the neurobiological basis for diversity of actions required to negotiate information-rich and dynamic environments for task goal attainment (Komar, Chow, Chollet, & Seifert, 2015; Rein, Davids, & Button, 2010; Seifert, Wattebled, Herault, Poizat, Adé, et al., 2014c; Seifert, Komar, Crettenand, & Millet, 2014b). These studies have shown that, more than simply ensuring stability against perturbations and adaptations to dynamic performance environments, the degenerate architecture of neurobiological systems can help individuals exhibit adaptability and creativity. Based on these ideas on neurobiological degeneracy, research on sport performance optimisation has begun to examine and to explain why expert performers often display high levels of intra- individual and inter-individual behavioural variability in sport, data traditionally viewed as counter-intuitive. The behavioural variability exhibited by skilled swimmers can play a functional role; for instance, it highlights an expert swimmer's capacity to perform several types of movement and/or to adopt one of a number of co-existing modes of coordination in order to achieve the same functional performance outcomes (swimming against waves or current, approaching the wall, preparing the turn, overcoming drag)(Guignard et al., 2017; Seifert, Komar, Barbosa, Toussaint, Millet, et al., 2014a). In the past years, empirical research on sport performance has clearly exemplified how intra-individual and inter-individual behavioural variability can play a functional role in swimming performance; however, these studies were limited to training and learning contexts (for a review, see Seifert, Komar, Barbosa, Toussaint, Millet, et al., 2014a). Therefore, the aim of our study was to consider cycle-to-cycle data set to investigate swimming speed (S) management and its subsequent stroking parameters (SR, stroke rate; SL, stroke length). More precisely, our study investigates the inter- and intra-individual variability of swimming speed (and its subsequent SR and SL) in top-level swimmers of a 50, 100 and 200-m freestyle National and World Championships, to determine individual profile of race management by using latent class mixed model, which is an innovative method coming from data mining.

Material and Methods

The performances of 32 top-level swimmers were video-analysed during the 50, 100 and 200-m freestyle finals of the Fédération Internationale de Natation Amateur (FINA) World Championships (Kazan, Russia, 2015) (8 males, 8 females) and the French National Championships (Montpellier, France 2016) (8 males, 8 females). The procedures (data collection and analysis) were approved by the French Federation of Swimming, FINA and the local University ethics committee, and conformed to the declaration of Helsinki. The procedures were explained to the swimmers, who then gave their written informed consent to participate.

The 50, 100 and 200-m freestyle events were videoed with a Black Magic 4K camera (25 Hz, Ultra HD, 3840×2160 pixels â Black Magic design, Melbourne, Australia) equipped with a 10-mm focal lens (f/4.5-5.6 IS STM) (âCanon Inc, Ôta, Tokyo, Japan) to visualize the entire pool (50 x 25 m). The camera was focused on the middle of the pool (25 m) and located in the top row of spectator seats approximately 25 m above and 15 m away from the side of the pool.

Race analysis software compiled in Matlab 2012 (The MathWorks, Inc., Natick, MA, USA) was used for calibration and image processing to obtain stroke rate (SR), stroke length (SL) and swim speed (S) for every stroke cycle. Four poolside marks in the swimming lane were chosen to calibrate the pool using 2D direct linear transformation algorithms (Abdel-Aaziz & Karara, 1971; Benarab, Napoléon, Alfalou, & Verney, 2017). The operator for each event made this calibration and then manually digitalized the head position at the beginning of each stroke cycle (right hand entry). The stroking phase was defined as the first and last right-hand entry after the start or underwater phase and before the turn in each lap. To quantify the reproducibility of the tracking procedure, the same race and same swimmer was digitalized ten times by eight operators. The root mean square (RMS) was calculated to estimate the tracking measure reproducibility (RMS = 0.0121 ± 0.0084 m).

The longitudinal analysis of speed was conducted on 32 swimmers for each 50-m lap in all races (50, 100 and 200-m freestyle). The speed dataset of each participant was normalized by the average speed of the race for all races events (to minimize the effect of gender and skill level, i.e. all males and females national and international swimmers were included). The latent class mixed model (LCMM) was used to identify trajectory classes of normalized speed over the different races. This model seeks potential latent profiles in heterogeneous populations. It combines a latent class model to identify homogenous latent classes of participants and a mixed model to describe the mean trajectory over the swimming race in each latent group, while taking account the individual correlation between repeated measures (Carrière et al., 2016). The trajectories of normalized speed were described using cubic spline functions without adjustment for baseline covariates. Cubic splines are piece-wise cubic polynomials smoothly assembled in the knot points (frequently, knots are located at suitably chosen quantiles). Not only pieces must connect but their slopes must match to ensure the curve is smooth. The shape of the class-specific and subject-specific trajectories were determined by comparing models with increasing number of model parameters (one to four knots in the spline functions, a diagonal or unstructured random-effect covariance matrix and a class-specific or proportional random-effect covariance matrix). The best model among models with the same number of classes (one- to four- latent classes) was selected using the Bayesian Information Criterion (BIC). The optimal number of latent class was determined by the BIC combined with the interpretability of the distinct classes. The longitudinal analysis allowed us to investigate the evolution of normalized speed in each latent class (decreased, stabilized or increased) for each lap. The classes size does not need to be identical. Finally, latent classes were characterized in terms of covariates (specialty, sex, distance race). The function HLME of the LCMM R-package version 1.7.6 was used to estimate the model parameters (Proust-Lima et al., 2015).

Results

The main findings of our study showed that the spline with three degrees of freedom was the best model to the normalized speed over the distance. This spline is composed by three pieces in each lap. Roughly, coefficients associated to spline components give us information about the first part of the race after the breakout (first movement after the underwater phases), the middle of the race and the turn in (approach to the wall before the flip turn) or to the end of the race (when the swimmer touches the wall).

Based on BIC and interpretability of the normalized values of speed (normalization is done by dividing absolute speed by the average speed on the race), two classes appeared for the 50-m race, then two classes for the first lap (L1) and one class for the second lap (L2) appeared for the 100 m race. Finally, two classes for L1 and L2 and three classes for L3 and L4 appeared for the 200-m race. When the raw values of speed were considered in respect to gender, two classes for male and four classes for female appeared in the 50-m race; three classes appeared for both gender in the 100 m race and four classes appeared for both gender in the 200-m race. These results (i.e., both the normalized and raw values of speed) suggested that longer was the race, higher was the number of classes i.e. higher was the variability of race management profiles, probably due to a strong effect of the turn-in and –out. This was well emphasized by the cubic spline model as the dominant class occurrence.

For the 50-m freestyle, the figure 1 showed two classes for the normalized values of speed: C1 with 25 swimmers (78.1% of the sample) and C2 with 7 swimmers (21.9% of the sample). The gender distribution inside each cluster was: 15 male and 10 female swimmers. Male swimmers have an average speed of 2.11 ± 0.04 $m.s^{-1}$ with a CV S of 5.43 ± 0.65 % while females have a lower average speed 1.89 ± 0.04 $m.s^{-1}$ and a CV S of 4.97 ± 0.76 %. Concerning C2, only 1 male and 6 female swimmers composed this cluster. The average absolute speed of the male was 2.13 $m.s^{-1}$ with a CV S of 2.84 % and the average speed for the female swimmers was 1.88 ± 0.03 $m.s^{-1}$ with a CV S of 3.28 ± 0.62 %. Based on the parameters of the model to cluster the swimmers, both C1 and C2 exhibited a quite stable speed after the dive, then a decrease of speed until the end of the race. As C2 started with a lower speed, its decrease of speed appeared lower than for C1 (Fig. 1).

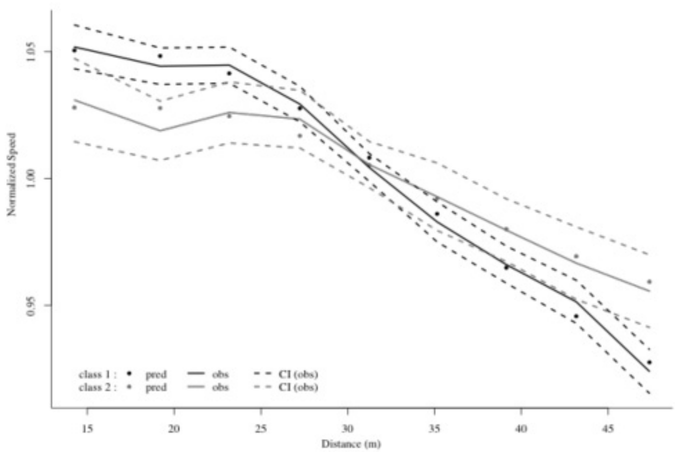


Figure 1. Normalized values of speed throw the 50-m freestyle. The black line corresponds to class 1 and the grey line to class 2, while the dashed lines correspond to their respective confidence interval (CI).

For the 100 m freestyle, the first lap (L1) was composed by two classes (Fig. 2 left panel): C1 represented 62.5% and C2 37.5% of the sample. The gender distribution inside each cluster was: 15 male and 5 female swimmers in C1. Male swimmers have an average speed of 2.05 ± 0.02 $m.s^{-1}$ with a CV S of 4.05 ± 0.53 %, while females have lower average speed 1.86 ± 0.03 $m.s^{-1}$ and a CV S of 3.69 ± 0.88 %. Concerning C2, only 1 male and 11 female swimmers composed this cluster. The average absolute speed for the male was 2.05 $m.s^{-1}$ with a CV S of 3.14 % while the average speed for female swimmers was 1.81 ± 0.02 $m.s^{-1}$ and a speed variation of 2.86 ± 0.60 %. At L1, swimmers from C1 swam faster after the start than swimmers of C2, but these later exhibited a slightly greater speed at the end of the lap when they approached the wall. C2 was characterized by an increase of speed after the start, then a quite constant speed until the middle of the lap and finally a decrease of speed.

At L2, all the swimmers were in the same class, showing a constant speed until the middle of the lap, and then a decrease of speed occurred (Fig. 2 right panel). The average speed was 1.89 ± 0.03 $m.s^{-1}$ with CV S equals to 4.91 ± 1.31 $m.s^{-1}$ for the 16 male swimmers while the average speed was 1.71 ± 0.03 $m.s^{-1}$ with 4.88 ± 0.76 % of speed variation for females.

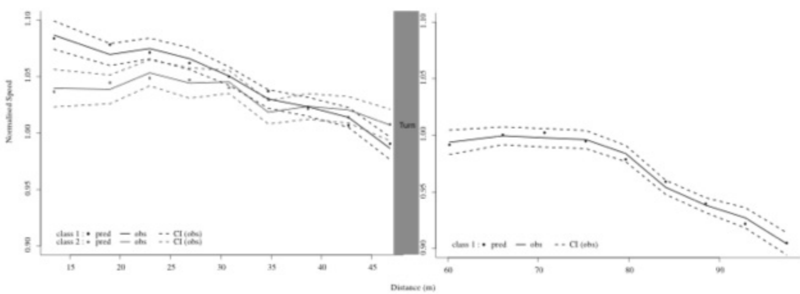


Figure 2. Normalized values of speed through the 100 m freestyle (left panel for L1 and right panel for L2). The black line corresponds to class 1 and the grey line to class 2, while the dashed lines correspond to their respective confidence interval (CI).

The mean values of S and the technical parameters (SR, SL, SI) with their standard deviation (*s.d.*) are summarized in Table 1 for the different classes of each lap, gender and of each race event (50, 100, 200-m freestyle). The Table 2 summarized the coefficient of variation (CV) for all parameters.

Race	Lap	Class	Gender	n	S	s.d.	SR	s.d.	SL	s.d.
50-m		1	M	15	2.11	0.04	60.95	1.70	2.08	0.04
		1	F	10	1.89	0.04	58.86	4.33	1.94	0.14
		2	M	1	2.13		60.18		2.13	
		2	F	6	1.88	0.03	58.12	2.40	1.94	0.08
100 m	L1	1	M	15	2.05	0.03	52.46	2.04	2.35	0.07
		1	F	5	1.86	0.03	50.99	2.97	2.20	0.16
		2	M	1	2.06		52.23		2.36	
		2	F	11	1.82	0.03	51.31	2.39	2.13	0.11
	L2	1	M	16	1.89	0.03	50.41	1.32	2.25	0.05
		1	F	16	1.71	0.03	49.45	2.41	2.09	0.10
200-m	L1	1	M	12	1.89	0.03	43.58	2.35	2.60	0.13
		1	F	16	1.72	0.03	45.60	2.79	2.27	0.13
		2	M	4	1.92	0.04	44.26	1.41	2.60	0.11
	L2	1	M	12	1.80	0.02	42.16	2.28	2.58	0.14
		1	F	15	1.65	0.02	43.52	3.06	2.28	0.15
		2	M	4	1.82	0.02	42.70	0.78	2.57	0.02
		2	F	1	1.68		40.38		2.49	
	L3	1	M	13	1.77	0.03	42.91	2.75	2.48	0.15
		1	F	10	1.60	0.02	42.98	1.68	2.23	0.09
		2	M	1	1.78		45.08		2.37	
		2	F	6	1.62	0.01	44.59	3.28	2.20	0.16
		3	M	2	1.78	0.01	43.90	1.01	2.43	0.03
	L4	1	M	8	1.73	0.05	44.91	2.16	2.32	0.13
		1	F	15	1.59	0.04	45.16	2.37	2.11	0.09
		2	F	1	1.60		43.57		2.21	
		3	M	8	1.74	0.05	46.67	2.15	2.25	0.11

Table 1. Average values of speed (S) and stroking parameters: stroke rate (SR), stroke length (SL) of the different classes for each lap, each race event (50, 100, 200-m freestyle) and for each gender (male, M and female, F). *n* is the number of swimmers in each class, and *s.d.* is the standard deviation.

Race	Lap	Class	Gender	n	CV S	s.d.	CV SR	s.d.	CV SL	s.d.
50-m		1	M	15	5.43	0.65	4.20	0.95	3.90	1.07
		1	F	10	4.97	0.76	4.15	1.16	4.03	0.67
		2	M	1	2.84		2.64		3.62	
		2	F	6	3.28	0.62	4.09	0.65	3.18	0.94
100 m	L1	1	M	15	4.06	0.53	4.49	1.66	3.63	0.95
		1	F	5	3.69	0.89	4.10	1.56	3.50	0.87
		2	M	1	3.15		2.43		3.48	
		2	F	11	2.86	0.60	4.53	1.70	4.64	1.44
	L2	1	M	16	4.91	1.31	3.47	0.95	4.64	1.15
		1	F	16	4.88	0.76	3.69	1.00	5.68	1.80
200-m	L1	1	M	12	3.68	0.83	3.95	1.40	3.86	1.05
		1	F	16	3.48	0.80	4.61	1.33	3.98	0.97
		2	M	4	6.55	1.22	4.73	0.50	4.62	0.99
	L2	1	M	12	3.20	0.60	4.01	2.63	4.51	2.05
		1	F	15	2.70	0.97	3.02	1.13	3.63	1.65
		2	M	4	4.30	1.20	3.88	1.79	4.58	1.65
		2	F	1	2.87		3.26		2.06	
	L3	1	M	13	3.62	1.14	3.34	1.40	4.35	1.08
		1	F	10	3.00	0.73	3.11	1.35	3.75	1.17
		2	M	1	2.54		2.20		3.07	
		2	F	6	2.41	0.58	2.64	1.14	2.98	0.84
		3	M	2	6.49	0.76	4.07	2.36	7.09	0.57
	L4	1	M	8	3.09	0.67	3.39	1.35	4.09	1.20
		1	F	15	3.27	1.08	2.65		4.29	1.94
		2	F	1	5.01		3.55	1.82	3.22	
		3	M	8	4.26	0.75	3.39	1.35	4.78	0.85

Table 2. Coefficient of variation (CV) of speed (S), stroke rate (SR) and stroke length (SL) of the different classes for each lap, each race event (50, 100, 200-m freestyle) and for each gender (male, M and female, F). *n* is the number of swimmers in each class, and *s.d.* is the standard deviation.

For the 200-m freestyle, two profiles of race management occurred at L1 and L2, while three profiles of race management appeared at L3 and L4.

At L1, two classes were identified as follows: C1 was composed by 28 swimmers (87.5% of the sample) and C2 was composed by 4 swimmers (12.5% of the sample). For C1, the speed decreased quite linearly until approaching of the wall. This cluster C1 was composed by 12 males with an average speed of 1.89 ± 0.03 $m.s^{-1}$ and the coefficient of variation of speed (3.63 ± 0.83 %) which were higher than those of the 16 female swimmers (S: 1.72 ± 0.03 $m.s^{-1}$ and CV S: 3.48 ± 0.80 %). Only 4 male swimmers composed C2 (S: 1.92 ± 0.04 $m.s^{-1}$ and CV S: 6.55 ± 1.22 %). The cluster C2 demonstrated a greater variability of speed and a faster start than C1. However, the speed further decreased than C2 from the middle to the end of the lap.

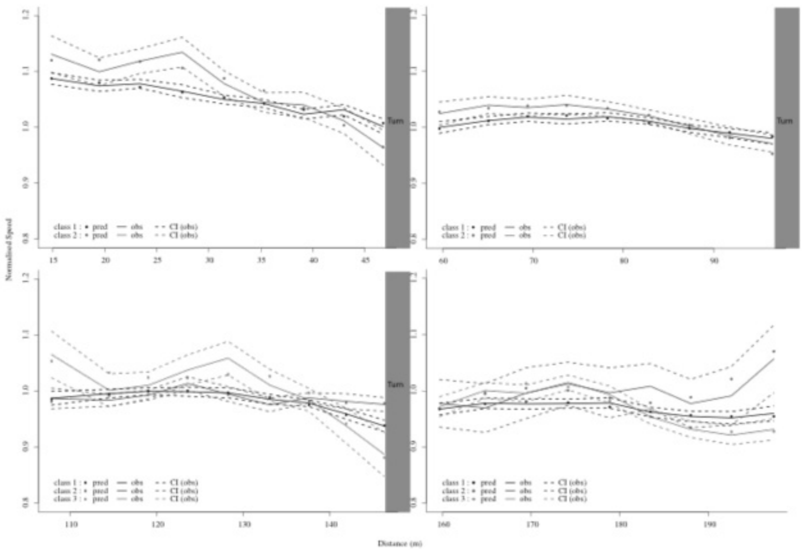


Figure 3. Normalized values of speed through the 200-m freestyle (upper left panel for L1; upper right panel for L2; lower left panel for L3 and lower right panel for L4). The black line corresponds to class 1, the grey line to class 2 and the light grey to class 3, while the dashed lines correspond to their respective confidence interval (CI).

In the second lap (L2), the first class C1 was composed by 84.3 % of the population. The 12 male swimmers have a greater average speed and CV S than the 15 females (S: 1.80 ± 0.02 vs.1.65 ±0.02 m.s-1 exponent and CV S: 3.20 ± 0.60 vs. 2.70 ± 0.97 % respectively) in the first class C1. The same tendency was founded in C2 with a 4 male and 1 female. (S: 1.82 ± 0.02 vs. 1.68 m.s-1 exponent and 4.30 ± 1.20 vs. 2.87 % respectively). The swimmers of C2 increased their speed after the turn and then they decreased it from 75-m to the wall. The lower variation of speed in

C1, revealed a quite constant speed until 80-m.

At the third lap (L3), three classes of swimmers were observed. Twenty swimmers (71.9 % of the sample) composed C1, including 13 males and 10 females. Males have higher speed and CV S than females (S: 1.77 ± 0.03 vs. 1.60 ±0.02 m.s-1 exponent and CV S: 3.62 ± 1.14 vs. 3 ±, 0.73 % respectively). The second class C2 exhibited 7 swimmers (21.8 % of the sample) with only 1 male and 6 females. These later demonstrated a lower speed and variation of speed (S: 1.78 vs. 1.62 ±0.01 m.s-1 exponent and 2.54 vs. 2.41 ± 0.58 % respectively). Only 2 male swimmers (6.3 %) composed the class C3 for whom S: 1.78 ±0.01 m.s-1 exponent and CV S: 6.49 ± 0.76 %. In C1, the speed stayed quite constant and decreased when the swimmer approached the wall. In C2, the speed stayed quite constant through the lap. The two swimmers of C3 decreased their speed after the turn, then their speed increased at the middle and decreased again at the end of the lap. In summary, this third lap showed three different profiles of race management: C3 exhibited a fast speed after the turn, a short increase and finally a great decrease of speed, which looks like a "zig-zag" management close to cubic model; C2 demonstrated a quite constant speed through the lap, reflecting a linear model; C1 exhibited a drop of speed at the end of the lap, reflecting a parabolic profile.

At L4, three classes of swimmers also occurred with similar profiles than observed at L3. The class C1 was composed by 23 swimmers (71.8 % of the sample) including 8 males with an average speed of 1.73 ± 0.05 m.s-1 and CV S of 3.09 ± 0.67 %, and 15 females with an average speed of 1.59 ± 0.04 m.s-1 exponent and a CV S of 3.27 ± 1.08 %. Those swimmers kept their speed almost constant until 180-m, and then they slightly decreased their speed until the end of the race. The class C2 was composed by only 1 female swimmer, who had an average speed of 1.60 m.s-1 exponent. Surprisingly she had a very high coefficient of variation of speed (5.01 %) and increased her speed until the end of the race. Finally, C3 was composed by 8 male swimmers with an average speed of 1.74 ±0.05 m.s-1 exponent and a high CV S: 4.26 ± 0.75 %. Those males increased their speed after the turn, slightly decreased it until 180-m and kept the speed almost constant until the end of the race. In sum, C3 exhibited an 'increase-decrease-slightly increase' of speed profile, reflecting a cubic model, while the quite constant speed of C1 could correspond to a linear model.

Discussion

The novelty of our approach was the use of latent class mixed model (LCMM) to investigate the intra- and inter-individual variability based on time series (i.e. cycle-to-cycle swimming speed) in competitive swimming. The coefficients associated to spline components gave us information about the different sections of the race: after the turn (i.e. arm strokes after the underwater phase of the turn-out), the middle section of the race (i.e. clean swimming part) and before the turn or the finish (i.e., approach of the wall).

The first main finding of our study was the similarity of race management and the low number of profiles (only two classes) observed for the first lap of 50, 100 and 200-m freestyle. In particular, the first profile demonstrated the capacity of swimming fast after the underwater phase of the start, which was followed by a high decrease of speed until the wall. Conversely, the second profile reflected a lower speed after the underwater phase of the start than the first profile but that remained more stable or even increased until the 25-m (for the 100 and 200-m), and then followed by a smaller decrease of speed than in the first profile. This second profile is well exemplified in figure 4 where the female S1 adopted the same race management for the 50-m and the first lap of the 100 m. Similarly, the male S3 adopted the same race management for L1 of the 100 m and the 200-m, and for L2 of the 100 m and the 200-m.

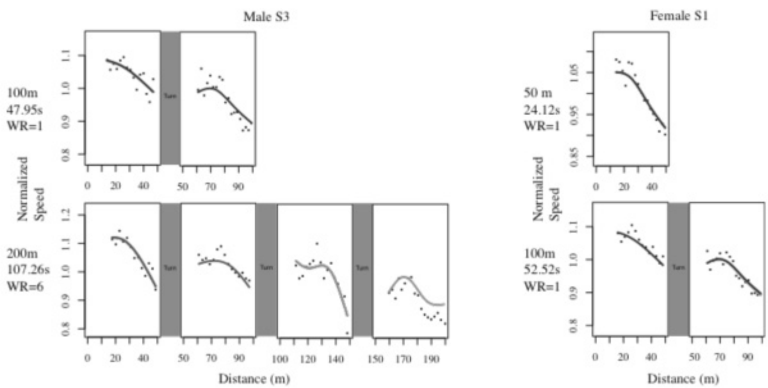


Figure 4. Normalized values of speed for two different freestyle races for the same swimmer: 100 m for S3 (upper left panel) and 200-m for S3 (lower left panel); 50-m for S1 (upper right panel) and 100 m (lower right panel).

The second main finding is the specificity of the race management for the 200-m; particularly the higher number of profiles (i.e. three classes) for the two last laps in comparison to the two first laps of the 200-m (i.e. two classes). Notably, it must be emphasized that only male swimmers composed the class C3, exhibiting the highest variation of speed with a fast speed after the turn and a great decrease of speed (for an example, see swimmer S3 in Fig. 5). The high variation of speed within the lap for the swimmers of C3 suggested an important effect of turn-in, turn-out, fatigue and/or a too fast start (this later could lead to great decrease of phosphocreatine). This class C3 suggested that higher was the swimming speed in comparison to the speed during the turn, more able were the swimmers to generate speed after the turn; however, it appeared hard to maintain this high speed to approach the wall.

The higher number of profiles for L3 and L4 of the 200-m also suggested that the swimmers might switch among various profiles between laps. For instance, the figure 5 exemplified three different profiles of race management of three international male swimmers (S1, S2 and S3) for the 200-m freestyle (Fig. 5).

Interestingly, those three international male swimmers showed close final time (106.81 ± 0.56 s) and high world ranking for the 200-m race between July 2015 and April 2016, suggesting that swimmers could exhibit similar performance outcome but with various race managements. The swimmer S2 managed his four laps in the same way (as they are all included in C1); those laps exhibited a quite stable or slightly increase of speed at the beginning of the lap, and then decrease of speed from the middle of the lap to the wall. Conversely, the swimmer S1 and S3 used the same speed management for L1 and L2; in particular a great decrease of speed, which was characterized by the class C2. Then, at L3 and L4, the swimmer S1 switched to C1 profile of management (i.e. a more stable speed within the lap than in C2 profile), whereas the swimmer S3 switched to C3 profile of management (i.e. an ‘increase-decrease’ of speed within the lap). These three examples suggested that (i) the swimmers could either maintain the same management all along the race or switch from one profile (let say one class of race management) to another profile (let say to another class of race management), and (ii) the swimmers could exhibited similarities of speed profile as they shared the same management for some laps of the race, but they could also showed differences of speed profile for other laps of the race. Interestingly, this inter-individual variability suggested that even at top level, various profiles of race management could coexist and could lead to high swimming speed, however without providing any prediction on winning the race.

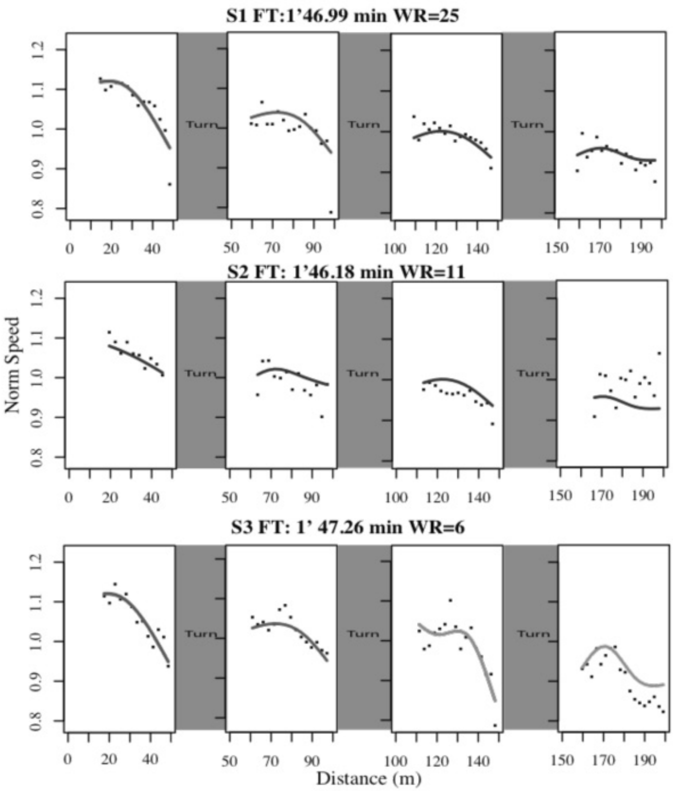


Figure 5. Trajectory of normalized values of speed for the four laps of the 200-m freestyle for three international male swimmers (S1, S2 and S3). The final time (FT) and the world ranking (WR) at the 200-m freestyle between July 2015 and April 2016. Black refers to the first class (C1), grey refers to the second class (C2) and light grey refers to the third class (C3).

In summary, our LCMM well emphasized that the different profiles of race management mainly related to in on hand the start, the turn and the finish effects (as already highlighted by Veiga and Roig (2016) and in another hand, the fatigue effect (as already mentioned by Aujouannet, Bonifazi, Hintzy, Vuillerme, & Rouard, 2006; Toussaint, Carol, Kranenborg, & Truijens, 2006). According to Veiga and Roig (2016), the speed at the start and at the turn was higher than the average speed (i.e. during the clean part of the swim) during the 100 m at the 2013 FINA World Championships. Our study reinforced those results by showing that some swimmers generated speed after the turn, but also lost speed when approaching the wall and turning. Our results confirmed the previous effect of turn (i.e. the turn itself but also the underwater phase after the turn until starting swimming) highlighted for instance by Elipot, Dietrich, & Hellard (2010), Houel, Elipot, André, & Hellard, (2013)Elipot, Dietrich, & Hellard (2010), Houel, Elipot, André, & Hellard, (2013) and Puel et al., (2012). Puel et al., (2012). However, our study also emphasized that there was not only one profile of race management as some swimmers exhibited a more linear management of the speed with a more or less constant speed or a more or less constant decrease of speed. It could be hypothesized that these different profiles of race management relate to the various profiles of turn and of underwater phase after the turn. For instance, Puel et al., (2012) suggested that longer wall push-off times could lead to faster velocities but mentioned that too much time spent on the wall could be directly prejudicial to performers by an increase of the turn time and a decrease of the overall performance. Therefore, there is not only one profile of turn, but instead the swimmers must find the best compromise to apply the highest force in the shortest turn time. This necessary compromise led to significant inter-individual variability of the turn time and turn distance during competition (e.g. Veiga & Roig, 2016). Similar results have been found about the effect of start on swimming speed (Seifert et al., 2010; Vantorre, Seifert, Fernandes, Vilas-Boas, & Chollet, 2010b; Vantorre, Seifert, Fernandes, Boas, & Chollet, 2010a). In particular, both for aerial and underwater phase, Seifert et al., (2010), Vantorre et al., (2010a) showed that different profiles could lead to similar short 15-m start time. For instance, to generate great take off speed, the swimmers must make a compromise between a long time spent on the block to create more force and a short time on the block to minimize the time deficit (Seifert et al., 2010).

A second hypothesis to understand higher inter-individual variability of race management of the 200-m freestyle related to fatigue (Figueiredo, Pendergast, Vilas-Boas, & Fernandes, 2013a), (Figueiredo, Rouard, Vilas-Boas, & Fernandes, 2013b). As already emphasized in previous publications, fatigue led the decrease in swimming speed that is related to a decrease in SL and in SR through the event (Alberty, Sidney, Pelayo, & Toussaint, 2009; Aujouannet et al., 2006; Sidney, Alberty, Leblanc, & Chollet, 2011; Toussaint et al., 2006) which was explained by a decrease in mechanical power output (e.g., 24% decrease of the mechanical power output was observed for the 100 m by Toussaint et al., (2006). Our results in table 1 confirmed this hypothesis as SL and SR decreased between laps. This decrease of SL and mechanical power output appeared concomitant with the decrease of anaerobic alactic contribution and the increase of aerobic contribution (Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes, 2010). The works simulated muscular metabolism (Mader, 2003),(Rodriguez & Mader, 2011) showed that relative rest phases such as during underwater phase after the turn (~9 to 10 s) could enable a partial recovery of phosphocreatine. From there, the high decrease of phosphocreatine during the first 50-m of the 200-m could explain the decrease of swimming speed(Rodriguez & Mader, 2011). At L2 and L3, the partial recovery of phosphocreatine during the turn as well as the higher contribution of aerobic system could explain the speed increase occurring until the middle of the lap (as observed in class C3). At L4 of the 200-m, the increase of the lactic anaerobic contribution until 80% (Rodriguez & Mader, 2011) associated to a decrease of the arm stroke efficiency and an increase of 16% of energy cost of locomotion Figueiredo, Pendergast, Vilas-Boas, & Fernandes (2013a),

Figueiredo, Rouard, Vilas-Boas, & Fernandes (2013b). Figuereido, Toussaint, Vilas-Boas, & Fernandes (2013c), (Figueiredo, Rouard, Vilas-Boas, & Fernandes, 2013b) could explain the decrease of speed observed in our study. The inter-individual variability observed for this energy system model (e.g. an increase of 40% of the standard deviation for the lactic anaerobic contribution in L4 of the 200-m; (Figueiredo et al., 2010) might also explain the inter-individual variability that we observed for the speed management. One hypothesis could be that the swimmers with high aerobic capacity could maintain a more constant swimming speed in comparison to swimmers with higher anaerobic contribution that could involve muscular fatigue and higher decrease of swimming speed at the end of L4.

In conclusion, our LCMM helped to explain and understand the effect of start, turn and finish, associated to fatigue, about the race management in competitive swimming. By distinguishing various profiles of race management in top elite swimmers, we emphasized the functional role of inter- and intra-individual variability because it might reflect continuous and dynamic interaction between an individual and the environment to achieve the task-goal. Indeed, according to the ecological dynamics framework (Davids, Araújo, Seifert, & Orth, 2015; Seifert et al., 2013; Seifert & Davids, 2012) the intertwined relationship between intentions, perceptions and actions constrains the direction and restrain the range of movement possibilities available for each individual performer. Thus, skilled swimmers showed the capacity to functionally adapt their behaviour by using a stable management or by being flexible (i.e. switching form profile to another profile) to satisfy these key constraints to achieve high performance outcome. Thus, our study suggested that expertise in swimming could be expressed through the relationship between behavioural flexibility (i.e., functional variability to adapt to a set of constraints) and stability (i.e., robustness of motor functions undergoing internal and external disturbances, such as fatigue) under interacting performance constraints (e.g., task, environment and personal)(Newell, 1986; Seifert et al., 2013; Warren, 2006). Skilled swimmers can individually and functionally adapt their race management during performance, exhibiting degenerate behaviours. Indeed, as already demonstrated in cognitive and perceptual-motor systems (Edelman & Gally, 2001; Mason, 2010; Price & Friston, 2002; Whitacre, 2010) the achievement of the same task-goal (i.e. to perform one function) by using various race management profiles (i.e. use of many behavioural structures) reflects the capacity to exploit degeneracy property in neurobiological system (Seifert et al., 2016). To explain this exploitation of degeneracy in race management, our hypothesis is that expert swimmers developed a more functional relationship with the performance environment, predicated on perception and action coupling. The development of expertise leads to the enhanced capacity for skilled performers to be attuned to functional properties of the environment (i.e. informational variable to approach the wall in order to turn without losing too much speed)(Davids et al., 2015; Fajen, Riley, & Turvey, 2009). This is because experts are more capable of exploiting information about environmental and task-related constraints to functionally (re)organise and regulate their behaviour, continuously, to achieve consistent performance outcomes.

Bibliography

Abdel-Aaziz, Y. I., & Karara, H. M. (1971). Direct linear transformation from comparator coordinates into object space coordinates in close-range photogrammetry (pp. 1–18). Presented at the ASP Symposium on close range photogrammetry, ASP Symposium on close range photogrammetry. http://doi.org/10.1080/10671188.1967.10616517

Alberty, M., Sidney, M., Pelayo, P., & Toussaint, H. M. (2009). Stroking Characteristics during Time to Exhaustion Tests. *Medicine & Science in Sports & Exercise*, *41*(3), 637–644. http://doi.org/10.1249/MSS.0b013e31818acfba

Aujouannet, Y. A., Bonifazi, M., Hintzy, F., Vuillerme, N., & Rouard, A. H. (2006). Effects of a high-intensity swim test on kinematic parameters in high-level athletes. *Applied Physiology, Nutrition, and Metabolism*, *31*(2), 150–158. http://doi.org/10.1139/h05-012

Benarab, D., Napoléon, T., Alfalou, A., & Verney, A. (2017). Optimized swimmer tracking system based on a novel multi-related-targets approach. *Optics and Lasers in Enginieering*, *89*, 195–202. http://doi.org/10.1016/j.optlaseng.2016.05.013

Bernstein, N. A. (1996). Dexterity and Its Development. (M. L. Latash & M. T. Turvey, Eds.). Mahwah, New Jersey: Lawrence Erlhaurn Associates Inc.

Carrière, I., Farré, A., Proust-Lima, C., Ryan, J., Ancelin, M. L., & Ritchie, K. (2016). Chronic and remitting trajectories of depressive symptoms in the elderly. Characterisation and risk factors. *Epidemiology and Psychiatric Sciences*, 1–11. http://doi.org/10.1017/S2045796015001122

Davids, K., Araújo, D., Seifert, L., & Orth, D. (2015). An ecological dynamics perspective. In J. Baker & D. Farrow (Eds.), *Routledge Handbook of Sport Expertise* (pp. 130–144). London.

Davids, K., Bennett, S., & Newell, K. M. (2006). Movement System Variability. Human Kinetics.

Edelman, G. M., & Gally, J. A. (2001). Degeneracy and complexity in biological systems. *Proceedings of the National Academy of Sciences of the United States of America*, *98*(24), 13763–13768. http://doi.org/10.1073/pnas.231499798

Elipot, M., Dietrich, G., & Hellard, P. (2010). High-level swimmers' kinetic efficiency during the underwater phase of a grab start. *Journal of Applied Biomechanics*, *26*(4), 501–507. http://doi.org/10.1123/jab.26.4.501

Fajen, B. R., Riley, M. A., & Turvey, M. T. (2009). Information, affordances, and the control of action in sport. *International Journal of ….*

Figueiredo, P., Pendergast, D., Vilas-Boas, J., & Fernandes, R. (2013a). Interplay of biomechanical, energetic, coordinative, and muscular factors in a 200 m front crawl swim. BioMed Research International Int, 897232. http://doi.org/10.1155/2013/897232

Figueiredo, P., Rouard, A., Vilas-Boas, J., & Fernandes, R. (2013b). Upper- and lower-limb muscular fatigue during the 200-m front crawl. Applied Physiology, Nutrition, and Metabolism, 38(7), 716–724. http://doi.org/10.1139/apnm-2012-0263

Figuereido, P., Toussaint, H. M., Vilas-Boas, J. P., & Fernandes, R. J. (2013c). Relation between efficiency and energy cost with coordination in aquatic locomotion. European Journal of Applied Physiology, 113(3), 651–9.

Foster, C., de Koning, J. J., Hettinga, F., Lampen, J., La Clair, K. L., Dodge, C., et al. (2003). Pattern of Energy Expenditure during Simulated Competition. *Medicine & Science in Sports & Exercise*, *35*(5), 826–831. http://doi.org/10.1249/01.MSS.0000065001.17658.68

Foster, C., deKoning, J. J., Hettinga, F., Lampen, J., Dodge, C., Bobbert, M., & Porcari, J. P. (2004). Effect of competitive distance on energy expenditure during simulated competition. *International Journal of Sports Medicine*, *25*(3), 198–204. http://doi.org/10.1055/s-2003-45260

Foster, C., Hendrickson, K. J., Peyer, K., Reiner, B., deKoning, J. J., Lucia, A., et al. (2009). Pattern of developing the performance template. *British Journal of Sports Medicine*, *43*(10), 765–769. http://doi.org/10.1136/bjsm.2008.054841

Foster, C., Snyder, A. C., Thompson, N. N., Green, M. A., Foley, M., & Schrager, M.

(1993). Effect of pacing strategy on cycle time trial performance. *Medicine & Science in Sports & Exercise*, *25*(3), 383-388. http://doi.org/10.1249/00005768-199303000-00014

Guignard, B., Rouard, A., Chollet, D., Hart, J., Davids, K., & Seifert, L. (2017). Individual–Environment Interactions in Swimming: The Smallest Unit for Analysing the Emergence of Coordination Dynamics in Performance? *Sports Medicine*, 1–13. http://doi.org/10.1007/s40279-017-0684-4

Hellard, P., Dekerle, J., Avalos, M., Caudal, N., Knopp, M., & Hausswirth, C. (2008). Kinematic measures and stroke rate variability in elite female 200-m swimmers in the four swimming techniques: Athens 2004 Olympic semi-finalists and French National 2004 Championship semi-finalists. *Journal of Sports Sciences*, *26*(1), 35–46. http://doi.org/10.1080/02640410701332515

Houel, N., Elipot, M., André, F., & Hellard, P. (2013). Influence of angles of attack, frequency and kick amplitude on swimmer's horizontal velocity during underwater phase of a grab start. *Journal of Applied Biomechanics*, *29*(1), 49–54.

Komar, J., Chow, J.-Y., Chollet, D., & Seifert, L. (2015). Neurobiological degeneracy: Supporting stability, flexibility and pluripotentiality in complex motor skill. *Acta Psychologica*, *154*, 26–35. http://doi.org/10.1016/j.actpsy.2014.11.002

Mader, A. (2003). Glycolysis and oxidative phosphorylation as a function of cytosolic phosphorylation state and power output of the muscle cell. *European Journal of Applied Physiology*, *88*(4), 317–338. http://doi.org/10.1007/s00421-002-0676-3

Mason, P. H. (2010). Degeneracy at Multiple Levels of Complexity. *Biological Theory*, *5*(3), 277–288. http://doi.org/10.1162/BIOT_a_00041

Mytton, G. J., Archer, D. T., Gibson, A. S. C., & Thompson, K. G. (2014). Reliability and Stability of Performances in 400-m Swimming and 1500-m Running. *International Journal of Sports Physiology and Performance*, *9*(4), 674–679. http://doi.org/10.1123/ijspp.2013-0240

Mytton, G. J., Archer, D. T., Turner, L., Skorski, S., Renfree, A., Thompson, K. G., & Gibson, A. S. C. (2015a). Increased Variability of Lap Speeds: Differentiating Medalists and Nonmedalists in Middle-Distance Running and Swimming Events. *International Journal of Sports Physiology and Performance*, *10*(3), 369–373. http://doi.org/10.1123/ijspp.2014-0207

Mytton, G. J., Archer, D. T., Turner, L., Skorski, S., Renfree, A., Thompson, K. G., & St Clair Gibson, A. (2015b). Increased variability of lap speeds: differentiating medalists and nonmedalists in middle-distance running and swimming events. *International Journal of Sports Physiology and Performance*, *10*(3), 369–373. http://doi.org/10.1123/ijspp.2014-0207

Newell, K. M. (1986). Constrains on the development of coordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor Develepment in Children Aspects of Coordination and Control* (pp. 341–360). Dordrecht.

Newell, K. M., & Corcos, D. M. (1993). Variability and motor control (pp. 1–12). Champaign:Human Kinetics Publishers.

Price, C. J., & Friston, K. J. (2002). Degeneracy and cognitive anatomy. *Trends in Cognitive Sciences*, *6*(10), 416–421. http://doi.org/10.1016/S1364-6613(02)01976-9

Proust-Lima, C., Philipps, V., & Liquet, B. (2015, March 3). Estimation of extended mixed models using latent classes and latent processes: the R package lcmm. *arXiv.org*.

Puel, F., Morlier, J., Avalos, M., Mesnard, M., Cid, M., & Hellard, P. (2012). 3D kinematic and dynamic analysis of the front crawl tumble turn in elite male swimmers. *Journal of Biomechanics*, *45*(3), 510–515. http://doi.org/10.1016/j.jbiomech.2011.11.043

Rein, R., Davids, K., & Button, C. (2010). Adaptive and phase transition behavior in performance of discrete multi-articular actions by degenerate neurobiological systems. *Experimental Brain Research*, *201*(2), 307–322. http://doi.org/10.1007/s00221-009-2040-x

Robertson, E. Y., Pyne, D. B., Hopkins, W. G., & Anson, J. M. (2009). Analysis of lap times in international swimming competitions. *Journal of Sports Sciences*, *27*(4), 387–395. http://doi.org/10.1080/02640410802641400

Rodriguez, F., & Mader, A. (2011). Energy systems in swimming. In L. Seifert, D. Chollet, & I. Mujika (Eds.), *World book of swimming: From Science to Performance* (pp. 225–240). New York: Nova Science.

Schmidt, R. A., & Lee, T. D. (2011). Motor Control and Learning (5 ed.). New York: Human Kinetics.

Seifert, L., & Davids, K. (2012). Intentions, perceptions and actions constrain functional intra-and inter-individual variability in the acquisition of expertise in individual sports. *Open Sports Sciences Journal*, *5*(Suppl 1-M8), 68–75.

Seifert, L., Button, C., & Davids, K. (2013). Key properties of expert movement systems in sport : an ecological dynamics perspective. *Sports Medicine*, *43*(3), 167–178. http://doi.org/10.1007/s40279-012-0011-z

Seifert, L., Komar, J., Araújo, D., & Davids, K. (2016). Neurobiological degeneracy: A key property for functional adaptations of perception and action to constraints. *Neuroscience and Biobehavioral Reviews*, *69*, 159–165. http://doi.org/10.1016/j.neubiorev.2016.08.006

Seifert, L., Komar, J., Barbosa, T., Toussaint, H., Millet, G., & Davids, K. (2014a). Coordination Pattern Variability Provides Functional Adaptations to Constraints in Swimming Performance. *Sports Medicine*, *44*(10), 1333–1345. http://doi.org/10.1007/s40279-014-0210-x

Seifert, L., Komar, J., Crettenand, F., & Millet, G. (2014b). Coordination Pattern Adaptability: Energy Cost of Degenerate Behaviors. *PLoS ONE*, *9*(9), e107839–9. http://doi.org/10.1371/journal.pone.0107839

Seifert, L., Vantorre, J., Lemaitre, F., Chollet, D., Toussaint, H. M., & Vilas-Boas, J. P. (2010). Different profiles of the aerial start phase in front crawl. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *24*(2), 507–516. http://doi.org/10.1519/JSC.0b013e3181c06a0e

Seifert, L., Wattebled, L., Herault, R., Poizat, G., Adé, D., Gal-Petitfaux, N., & Davids, K. (2014c). Neurobiological Degeneracy and Affordance Perception Support Functional Intra-Individual Variability of Inter-Limb Coordination during Ice Climbing. *PLoS ONE*, *9*(2), e89865–12. http://doi.org/10.1371/journal.pone.0089865

Sidney, M., Alberty, M., Leblanc, H., & Chollet, D. (2011). Stroking Parameters during Competition. In *World book of swimming: From Science to Perfor-*

mance (pp. 443–458). Nova Science.

Summers, J. J., & Anson, J. G. (2009). Current status of the motor program: Revisited. *Human Movement Science*, *28*(5), 566–577. http://doi.org/10.1016/j.humov.2009.01.002

Thompson, K. (2015). Pacing:Individual Strategies for Optimal Performance. Champaign, Illinois: Human Kinetics.

Thompson, K. G., Haljand, R., & MacLaren, D. P. (2000). An analysis of selected kinematic variables in national and elite male and female 100- m and 200-m breastroke swimmers. *Journal of Sports Sciences*, *18*(6), 1–13. http://doi.org/10.1080/02640410050074359

Thompson, K. G., MacLaren, D. P., Lees, A., & Atkinson, G. (2004). The effects of changing pace on metabolism and stroke characteristics during high-speed breaststroke swimming. *Journal of Sports Sciences*, *22*(2), 149–157. http://doi.org/10.1080/02640410310001641467

Tononi, G., Sporns, O., & Edelman, G. M. (1999). Measures of degeneracy and redundancy in biological networks. *Proceedings of the National Academy of Sciences of the United States of America*, *96*(6), 3257–3262. http://doi.org/10.1073/pnas.96.6.3257

Toussaint, H. M., Carol, A., Kranenborg, H., & Truijens, M. J. (2006). Effect of Fatigue on Stroking Characteristics in an Arms-Only 100 m Front-Crawl Race. *Medicine & Science in Sports & Exercise*, *38*(9), 1635–1642. http://doi.org/10.1249/01.mss.0000230209.53333.31

Tucker, R., & Lambert, M. I. (2006). An analysis of pacing strategies during men's world-record performances in track athletics. *International Journal of Sports Physiology and Performance*.

Vantorre, J., Seifert, L., Fernandes, R. J., Boas, J. P. V., & Chollet, D. (2010a). Kinematical profiling of the front crawl start. *International Journal of Sports Medicine*, *31*(1), 16–21. http://doi.org/10.1055/s-0029-1241208

Vantorre, J., Seifert, L., Fernandes, R. J., Vilas-Boas, J. P., & Chollet, D. (2010b). Comparison of Grab Start between Elite and Trained Swimmers. *International Journal of Sports Medicine*, *31*(12), 887–893. http://doi.org/10.1055/s-0030-1265150

Veiga, S., & Roig, A. (2016). Effect of the starting and turning performances on the subsequent swimming parameters of elite swimmers. *Sports Biomechanics*, *16*(1), 34–44. http://doi.org/10.1080/14763141.2016.1179782

Warren, W. H. (2006). The dynamics of perception and action. *Psychological Review*, *113*(2), 358–389. http://doi.org/10.1037/0033-295X.113.2.358

Whitacre, J. M. (2010). Degeneracy: a link between evolvability, robustness and complexity in biological systems. *Theoretical Biology and Medical Modelling*, *7*(1), 6. http://doi.org/10.1186/1742-4682-7-6

Acute effects of various post-activation potentiation protocols on 15-m and 25-m freestyle swimming

Daniel Juárez Santos-García[1], Enrique Alonso Plaza[1] and José María González Ravé[1].

Introduction

The phenomenon of post-activation potentiation (PAP) has been a topic of considerable interest in recent years (Docherty, Robbins and Hodgson, 2004; Ebben and Watts, 1998), with its foundations being the following: exercise with heavy loads increases motor neuron excitability and the reflection of potentiation, which can create optimal conditions for subsequent exercise (Chu, 1996; Fees, 1997; Fleck and Kontor, 1986). A possible explanation for this phenomenon is the improvement in prestimulation of motor neuron excitability (increased recruitment of motor units, better synchronisation or reduction in presynaptic inhibition) (Aagaard, 2003; Aagaard, Simonsen, Andersen, Magnusson and Dyhre-Poulsen, 2002; Gullich and Schmidtbleicher, 1996; Trimble and Harp, 1998). In this respect, PAP could be a strategy to improve performance in various sports. However, although there are clear benefits to using this principle as a long-term training intervention, there is also the potential of incorporating it into a warm-up prior to performance (Matthews, Matthews and Snook, 2004).

The power developed during swimming is a fundamental aspect (especially in the specialties that include associated short tests) for achieving optimal performance in competition, due to its close relationship with swimming speed and, consequently, the time needed to complete the distance (González-Ravé et al., 2011). Systems and elements that enable the implementation of greater swimming resistance have traditionally been employed to develop specific swimming strength (Girold, Camels, Maurin, Milhau and Chatard 2006, 2007; Patnott, Post and Northius, 2003; Wright, Bramer and Stager, 2009).

Girold et al. (2006) indicated that sprint training with resistance bands in swimming was more effective than traditional training or assisted sprint, improving times in the 100 m freestyle and enhancing muscle

1. Sport Training Lab, Faculty of Sport Sciences, University of Castilla-La Mancha, Spain.

strength and power. These studies refer to training consisting of several sessions; however, there are few studies on the acute effects of a single session in swimming. Kilduff et al. (2011) observed that after a series of three repetitions at 87% of 1-repetition maximum, there were no differences in the times for the 15-m swim length at maximum velocity. Juárez et al. (2013) found no significant differences in the times for the 25 m length after various tasks were performed 30 s before swimming (rubber band traction for 10 s, 12 m of swimming with 30% of 1-repetition maximum resistance in this task). Each group repeated this protocol on four occasions, with 2 minutes of rest between repetitions. No significant differences were found either between the various groups or between the repetitions performed by each group.

Another study with swimmers (Cuenca-Fernández, López-Contreras and Arellano, 2015) compared two PAP protocols on launch performance. In the first protocol, the swimmers performed three lunges at 85% 1-repetition maximum. In the second, they performed four repetitions simulating the launch in swimming but using a Yo-Yo device. The study found better performance results in the launch with the latter protocol. On the other hand, Sarramian, Turner and Greenhalgh (2015) compared the effect of 4 types of warm-up on 50-m freestyle times: traditional warm-up, PAP focused on the upper body, PAP focused on the lower body and combined PAP. The authors observed that a traditional warm-up achieved better times when compared with the upper body PAP warm-up, with no significant differences between the rest of the warm-ups. However, when the data were analysed according to sex, the authors found that the men achieved better times with the upper body PAP warm-up than with the traditional warm-up or combined PAP.

In this respect, more studies are needed to analyse these issues, considering the importance that any meaningful improvement, even small, has for short tests. Therefore, the objectives for this study were the following: (i) to analyse the acute responses caused by various tasks with high loads (semi-squat, pulldown to the chest and both) compared with traditional warm-up in the swim speed for 15 m and 25 m; and (ii) to analyse the differences in the implementation of this method according to sex. The hypotheses were the following: (i) performing tasks with heavy loads beforehand positively influences the swimming times in the 15- and 25-m lengths; and (ii) applying the PAP training method produces the same effects regardless of sex.

Materials and methods

Participants

Ten swimmers participated in the study: six men and four women (mean age, 16.5 ± 1.8 years; mean weight, 67.75 ± 6.89 kg; mean height, 177.90 ± 8.08 cm). All the swimmers were national-level athletes, having participated in the Spanish Championship in their category during the season in which the study was conducted. All were finalists, and four of them had won a medal in this competition. At the time when the study was conducted, the swimmers trained six times a week, with 2 hours of training in the swimming pool and three days of dry training (gym) of approximately 1 hour. All the swimmers had accumulated five to seven years of high-performance training. The swimmers, their trainers and the swimmers' parents were informed of the study characteristics. All the parents signed an informed consent document. The study was conducted according to the Declaration of Helsinki.

Procedure

The study participants conducted five assessment sessions. The first session determined the 6-repetition maximum in semi-squat and lat pulldown, increasing the weight until the swimmers were no longer able to perform more than six repetitions with a specific load. These two exercises were selected because they were standard upper- and lower-limb exercises for these swimmers. In a subsequent session, the swimming times for 25 m were recorded (with partial measurement in the 15 m) after a standard swimming warm-up for these swimmers: 200 m of swimming, 4 x 50 m legs, 4 x 50 m (25 sculling/25 swimming), 4 x 25 m changes in pace, 4 x 25 m progressive and 100 m smooth. The times were recorded manually by a trained expert with a stopwatch.

In the third session, all the swimmers performed a 6-repetition maximum series of semi-squats, which, according to the Brzycki prediction equation (1993), represents 86.1% of 1-repetition maximum. After 8 min of recovery (Bewan et al., 2009; Kilduff et al., 2011, Cuenca-Fernández et al., 2015), the times for 25 m were recorded (with a partial measurement at 15 m) to observe the direct influence of a leg strength exercise on swimming speed. In the fourth session, the swimmers performed a 6-repetition maximum series of lat pulldowns. Eight minutes later, they performed 25 m of swimming at maximum speed. In the last study session, the swimmers performed a 6-repetition maximum series of squats followed by 6-repetition maximum in lat pulldown and, after 8 min, 25 m of swimming. In this last session, half of the swimmers started with the squat series, and the other half started with the lat pulldowns, in a randomised manner. Passive recovery was performed in all sessions.

Statistical analysis

The SPSS v.19.0 statistical program was employed for the data analysis. We calculated the means and standard deviations of the study endpoints. The normality of the sample was checked with the Shapiro-Wilk test. To analyse the differences in the 15- and 25-m times among the various measurements, we applied a one-way, repeated measures analysis of variance (ANOVA), establishing a significance level of $p<.05$. To analyse the differences according to sex, we applied a two-way repeated measures ANOVA (warm-up condition and sex), verifying the homogeneity of variances using Levene's test. In addition, a partial eta squared (η^2) was calculated as an index of effect size, and was interpreted as small (0.01), moderate (0.06) and large (0.14) (Cohen, 1988).

Results

The mean weight lifted in the 6-repetition maximum in the semi-squat test was 74.5 ± 13.3 kg, whereas the mean weight in the 6-repetition maximum in the lat pulldown test was 63.0 ± 9.2 kg. Table 1 shows the results for the 15 m and 25 m. There were no differences in the times after each of the tasks in the 15 m (η^2=0.08). However, we observed a difference ($p<.01$; η^2=0.43) between the time in the 25 m after the 6-repetition maximum lat pulldown task and the time in the 25 m after the 6-repetition maximum semi-squat plus 6-repetition maximum pulldown task. When analysing the results according to sex, we found that in no case there were differences (sex x warm-up condition) in time in the 15 m (η^2=0.07) and 25 m (η^2=0.04) in each of the evaluation sessions for either the men or the women. However, if sex is the only factor considered, we found a partial eta square of 0.15 for the 15 m and 0.09 for the 25 m.

Task	Participants	15 m mean ± SD	25 m mean ± SD
Traditional warm up	All subjects (N=10)	7.05 ± 0.71	12.75 ± 1.21
	Men (N=6)	6.84 ± 0.66	12.48 ± 1.30
	Women (N=4)	7.37 ± 0.75	13.16 ± 1.11
6-repetition maximum Squat	All subjects (N=10)	7.03 ± 0.79	12.78 ± 1.26
	Men (N=6)	6.85 ± 0.77	12.53 ± 1.39
	Women (N=4)	7.30 ± 0.86	13.16 ± 1.10

6-repetition maximum Pulldown	All subjects (N=10)	6.96 ± 0.67	12.62 ± 1.09
	Men (N=6)	6.74 ± 0.64	12.37 ± 1.20
	Women (N=4)	7.31 ± 0.62	12.99 ± 0.94
6-repetition maximum Squat + 6-repetition maximum Pulldown	All subjects (N=10)	7.04 ± 0.72	12.83 ± 1.13
	Men (N=6)	6.80 ± 0.63	12.54 ± 1.18
	Women (N=4)	7.40 ± 0.78	13.27 ± 1.03

Table 1. Time in the 15 m and 25 m after each task.

Discussion

Our aims were to analyse the acute responses caused by various tasks with heavy loads (semi-squat, lat pulldown and both) compared with traditional warm-up in the swim speed for 15 m and 25 m and to compare the results according to sex. We found no improvements in the times for the 15- and 25-m lengths at maximum speed after previously performing one or several strength exercises with heavy loads prior to swimming when compared with the implementation of a traditional warm-up. This result is in line with Sarramian et al. (2015) who found no differences in the times for the 50-m freestyle after a traditional warm-up compared with various PAP warm-ups, observing in some cases better times after the traditional warm-up. First, we must consider the task performed, because it was not an explosive action such as a swimming start, but rather a longer-lasting action. Although it was also not a task with the duration of a 15-m or 25-m swimming sprint, we have in any case shown that the complex method could be interesting for improving sprint performance.

Matthews et al. (2004) investigated the acute effect of a pre-competition resistance training warm-up on subsequent 20-m sprint performance, observing improvements in 20-m sprints after a 5-repetition maximum in squats in rugby players. Despite involving a similar distance to those evaluated in our study, in that case, the 20-m sprints are in running and not in swimming. Gullich and Schmidtbleicher (1996) and González-Ravé et al. (2009) stated that the potentiation phenomenon is only effective when the participants were experts and belong to a professional group. The current study supports this statement, given that the selected sample was not an elite group. In contrast Young et al. (1998) and Evans et al. (2000) obtained gains in potentiation work with midlevel participants, although the participants did have experience in working with loads. This differs partially from our study because our participants who performed the squat and those who performed the 6-repetition maximum did not typically work with heavy loads.

The intensity of the load employed in our study was 86.1% of 1-repetition maximum (6-repetition maximum). Kilduff et al. (2011) worked with three repetitions at 87% of 1-repetition maximum in swimming, obtaining significant improvements at 8 min in the countermovement jump but not in the 15-m sprint. This finding is within the 75%–85% margin of 1-repetition maximum (Radcliffe and Radcliffe, 1996) needed to promote potentiation, although it is true that these authors proposed four sets of four repetitions versus the single sets of six repetitions that was performed in the present study. However, our study is supported by studies that obtained PAP improvements with a single set of 5-repetition maximum (Young et al., 1998; Evans et al., 2000; Matthews et al., 2004; Scott and Docherty, 2004).

There is no clear evidence of a different functioning of the PAP mechanism between men and women. It is difficult to compare differences due to the limited samples and availability of women participants. The number of studies that treat both groups and establish differences is limited. It has been suggested that the PAP mechanism could be more effective in men (Radcliffe and Radcliffe, 1996). A study by Sarramian et al. (2015) observed that men achieved better times in the 50 m freestyle after an upper-body PAP warm-up compared with a combined PAP warm-up or a traditional warm-up. In our study, although no differences were observed, the large and moderate effect sizes according to sex, of 15 m and 25 m, respectively, can suggest the possibility of differences between sex, if studied with a large sample. In any case, it is unclear whether this phenomenon affects men and women differently (O'Leary, Hope, and Sale, 1998).

Conclusions

We can state that there are no significant differences in the times for the 15 m and 25 m freestyle at maximum speed after performing the various tasks with heavy loads (semi-squat, lat pulldown and both) 8 min before swimming. We can therefore confirm that there is insufficient scientific evidence to confirm that the PAP exercise with these characteristics improves speed performance in a 25-m swimming test. There are no significant differences according to sex in the recorded sessions or in the 15- and 25-m lengths. There is therefore no apparent difference in the functioning of the PAP mechanism between men and women, considering the study characteristics.

References

Aagaard, P. (2003). Training induced changes in neural function. Exercise and Sport Science Review 31(2), 61-67.

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P. and Dyhre-Poulsen, P. (2002). Neural adaptations to resistance training: evoked V-wave and H-reflex responses. Journal of Applied Physiology 92(6), 2309-2318.

Bevan, H.R., Owen, N.J., Cunningham, D.J., Kingsley, M.I.C. and Kilduff, L.P. (2009). Complex training in professional rugby players influence of recovery time on upper-body power output. Journal of Strength and Conditional Research 23(6), 1780–1785.

Brzycki, M. (1993) Strength testing-predicting a one-rep max from reps-to-fatigue. JOPERD, 68: 88-90.

Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2ª ed). NewYork: Academic Press.

Chu, D. A (1996). Explosive power and strength: complex training for maximum results. Champaign: Human Kinetics.

Cuenca-Fernández, F., López-Contreras, G. and Arellano, R. (2015). Effect on swimming start performance of two types of activation protocols: lunge and YoYo squat. Journal of Strength and Conditioning Research, 29(3): 647-655.

Docherty, D., Robbins, D., and Hodgson, M (2004). Complex training revisited: a review of its current status as a viable training approach. Strength and Conditioning Journal 26(6), 52-57.

Ebben, W. P. and Blackard, D. O. (1998). Paired for strength: a look at combining weight training with plyometric exercises with a focus on vertical jump improvement. Training and Conditioning 8(3), 55-63.

Evans, A.K., Hodgkins, T.D., Durham, M.P., Berning, J.M. and Adams, K.J. (2000). The acute effects of a 5RM bench press on power output. Medicine and Science in Sports and Exercise 32(5), 312.

Fees, M.A. (1997). Complex training. Athletic therapy today 2(1), 18.

Fleck, S.J. and Kontor, K. (1986). Complex training. National Strength and Conditioning Association Journal 8(5), 66-68.

Girold, S., Camels, P., Maurin, D., Milhau, N. and Chatard, J.C. (2006). Assisted and resisted sprint training in swimming. Journal of Strength and Conditional Research 20(3), 547-554.

Girold, S., Camels, P., Maurin, D., Milhau, N. and Chatard, J.C. (2007). Effects of dry-land vs. resisted and assisted sprint exercise on swimming sprint performance. Journal of Strength and Conditional Research 21(2), 599-605.

González-Ravé, J.M., Machado, L., Navarro-Valdivielso, F. and Vilas-Boas, J.P. (2009). Acute effects of heavy-load exercises, stretching exercises, and heavy-load plus stretching exercises on squat jump and countermovement jump performance. Journal of Strength and Conditional Research 23(2), 472–479.

González-Ravé, J.M., Juárez, D., Clemente, V., Muñoz, V., Díaz, G., Carrasco, M. and Navarro-Valdivielso, F. (2011). Análisis de la potencia máxima específica en nadadores de diferente nivel. Revista de Entrenamiento Deportivo 25(3), 11-15.

Gullich, A. and Schmidtbleicher, D. (1996). MVC-induced short-term potentiation of explosive force. New Studies in Athletics 11(4), 67-81.

Juárez, D., González-Ravé, J. M., Legaz, A., Portillo, J., Clemente, V. and Newton, R. U. (2013). Acute effects of two resisted exercises on 25m swimming performance. Isokinetics and Exercise Science, 21(1): 29-35.

Kilduff, L.P., Cunningham, D.J., Owen, N.J., West, D.J,. Bracken, R.M. and Cook, C.J. (2011). Effect of postactivation potentiation on swimming starts in international sprint swimmers. Journal of Strength and Conditioning Research 25(9), 2418-2423.

Matthews, M.J., Matthews, H.P. and Snook, B. (2004). The acute effects of a resistance training warm up on sprint performance. Research in Sports Medicine 12(2), 151-159.

O'Leary, D.D., Hope, K. y Sale, D.G. (1998). Influence of gender on post-tetanic potentiation in human dorsiflexors. Canadian Journal of Physiology and Pharmacology 76(7-8), 772-779.

Patnott, J.R., Post, K. and Northius, M.E. (2003). Muscular power changes in collegiate swimmers. Medicine and Science in Sports and Exercise 35(5). Supplement abstract 1454.

Radcliffe, J.C. and Radcliffe, J.L. (1996). Effects of different warm-up protocols on peak power output during a single response jump task. Medicine and Science in Sports and Exercise 28(5), 189.

Sarramian, V.G., Turner, A. and Greenhalgh, A.K. (2015). Effect of postactivation potentiation on fifty-meter freestyle in national swimmers. Journal of Strength and Conditioning Research, 29(4): 1003-1009.

Scott, S. and Docherty, D. (2004). Acute effects of heavy pre-loading on vertical and horizontal jump performance. Journal of Strength and Conditioning Research 18(2), 201-205.

Trimble, M. and Harp, S. (1998). Postexercise potentiation of the H-reflex in humans. Medicine and Science in Sports and Exercise 30(6), 933-941.

Wright, B.V., Bramer, C.L. and Stager, J.M. (2009). Five-week assessment of in water output in competitive swimmers. ACSM 56th. Annual Meeting, Seattle, Washington.

Young, W.B., Jenner, A. and Griffiths, K. (1998). Acute enhancement of power performance from heavy load squats. Journal of Strength and Conditioning Research 12(2), 82-84.

Altitude training for sea level performance: a systematic review

Ferran A. Rodríguez[1] and Sergi Àvila[1]

Introduction

Altitude training (AT) at natural environment has been a matter of extensive research for half a century and, despite some sceptical views (1-3), it continues to play an important role in the preparation of elite and sub-elite athletes in many countries (4, 5). Paradoxically, there is a remarkable lack of controlled and adequately powered studies on natural AT in the scientific literature, particularly in elite athletes, and there is no clear evidence that AT enhances performance more than training at sea level (SL) (1, 5-7). The theoretical concept behind this practice is the independent and combined effects of the physiological processes of acclimatization to chronic hypoxia and those derived from training under the additional stress imposed by exercising in a hypoxic environment (8). In accordance with some investigations, altitude acclimatization results in central and peripheral adaptations, i.e. augmented red cell volume, haemoglobin (Hb) mass and maximal oxygen uptake ($\dot{V}O_{2max}$) that improve primarily systemic oxygen delivery ("erythropoietic paradigm") (9, 10), while others argue against this view and support the concept of "nonhematological" adaptations such as improved muscle efficiency, greater muscle buffering and the ability to tolerate lactic acid production (11, 12).

Conversely, the combination of intense training and hypoxia may have a negative impact on athlete's performance capacity and health status, causing unfavourable effects such as acute mountain sickness (13), immune suppression (14), iron-deficient erythropoiesis (15), cathecolamine mediated glycogen depletion (16) and increased oxidative stress and tissue damage (17), among others. Interestingly, a recent meta-analysis concluded that AT performance gains could be related to a placebo or nocebo effect (7).

There are different strategies to train at altitude. The classical approach ("live high-train high", Hi-Hi), used since the late 1960s, involves

1. INEFC-Barcelona Sport Sciences Research Group, Institut Nacional d'Educació Física de Catalunya (INEFC), Universitat de Barcelona, Spain

SL-resident athletes who travel to and subsequently live and train at moderate altitude. Despite being used by many elite swimmers and coaches, there is no clear evidence that training at natural altitude enhances performance more than training at SL (6). In a milestone study published in the mid-1990s, Levine & Stray-Gundersen provided evidence that the "live high-train low" (Hi-Lo) strategy can improve 3000- to 5000-m running performance in collegiate/club runners (9). Later, this approach was modified to limit the low-altitude training sessions to only high-intensity workouts and was subsequently termed "live high-train high and low" (Hi-HiLo). The improvement in running performance was associated with increase in red cell mass, the subsequent increase in maximal oxygen uptake ($\dot{V}O_{2max}$), the "high altitude effect", and the maintenance of high-intensity training velocities and oxygen flux to the muscles "the low altitude effect" (18). This paradigm has been sustained by later investigation in elite endurance athletes performing different sports including running (19), orienteering (20), and cycling (21). However, these studies are difficult to compare with each other directly given the many differences in experimental design (12).

The aims of this systematic review are: 1) to collate and to critically evaluate the empirical evidence sustaining the use of natural AT in athletes with the main goal of improving SL performance; and 2) to derive which of the different natural AT strategies is more efficient for enhancing SL performance when the athletes come back to SL training and competition. To achieve these goals, we systematically reviewed controlled and uncontrolled studies through the PubMed and SPORTDiscus databases. The studied participants were athletes from regional to elite level, the exposure of interest was natural AT, and the main outcome of interest was performance.

Methods

Literature search

This systematic review followed the PRISMA statement guidelines (22). To achieve this, a systematic literature search was conducted for studies in any language indexed in the PubMed and SPORTDiscus databases (up to March 2017). This search was performed using the following selected keywords: ALL FIELDS, altitude training AND sport AND performance, NOT simulated OR artificial OR normobaric, NOT review. To manage the bibliographic references the EndNote (ver. X7) software was used.

Eligibility criteria and study selection

In order to be considered eligible for inclusion, studies had to meet the following criteria: 1) participants were healthy adult competitive athletes; 2) studies were controlled and uncontrolled; 3) altitude exposure was natural (classic or terrestrial, not artificial or simulated); 4) primary focus was SL performance (articles with no performance measures were excluded); 5) original studies were used only (no reviews); and 6) studies published in any language.

The flow chart of literature screening approach and study identification is displayed in figure 1. From the 325 articles initially identified, we removed 51 duplicated articles, 224 were excluded from title and abstract information, and 30 articles were excluded after reading the full text for not meeting the eligibility criteria or due to impossibility to access them. Finally, 20 studies were included in the qualitative review.

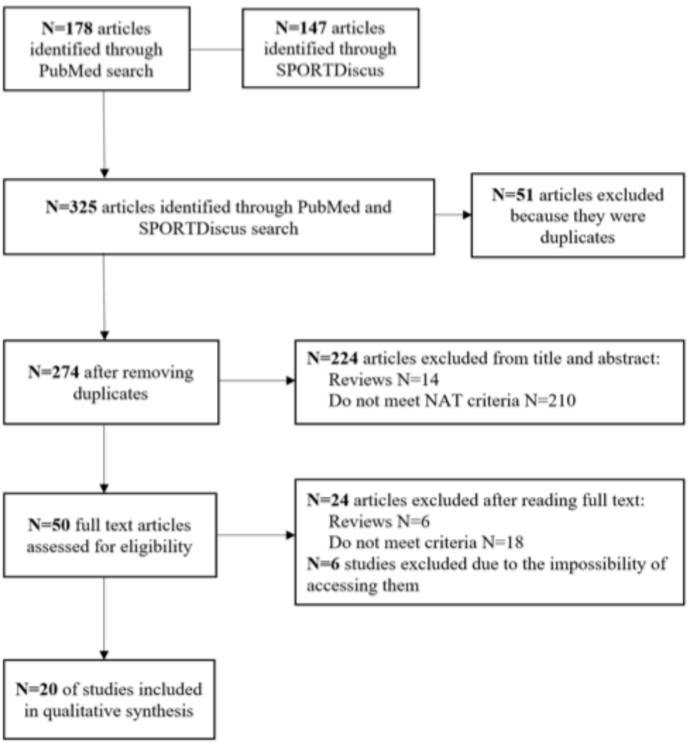


Figure 1. Flow chart of literature screening approach and study identification.

Data extraction

We developed a data extraction table classifying the type/level of athletes, altitude strategy, sample size, study design, follow up during the intervention, living and training characteristics and effects on performance measures. Performance data extraction was done from time trials, race results, power output and total work capacity (cycle ergometry) and time scores. Weight-adjusted $\dot{V}O_{2max}$ values and selected haematological data (Hb mass, Hb blood concentration and haematocrit ratio) were also extracted.

Results

Study characteristics

A total of 20 studies, 7 controlled and 13 uncontrolled, were identified for inclusion in the systematic review. These studies involved 439 athletes, from which 173 took part in the controlled studies and 266 in the uncontrolled studies. 247 out of the total 439 participants were elite athletes (56%), and the rest were from regional/interregional to subelite level athletes (44%), a fact that can bring about large differences in performance level and range for improvement, making difficult to compare investigation results. The intervention methodologies and type of designed utilized were as follows: 14 Hi-Hi (5 controlled), 4 Hi-Lo (3 controlled), and 3 Hi-HiLo (1 controlled

Classical altitude training (Hi-Hi) controlled studies

Only 5 controlled Hi-Hi studies were identified (table 1). Using a cross-over design, Adams et al. reported no potentiating effect of hard endurance training at 2300 m over equivalent SL training on 2-mile performance time or $\dot{V}O_{2max}$ in well-conditioned middle-distance runners (23) The study by McLean et al. consisted on a Hi-Hi training camp involving a group of 21 Australian football players and 9 Lo-Lo controls. The Hi-Hi group likely improved 2000-m time trial performance by 1.5% after altitude with very large individual variability (90%CI: -3.3–6.3%) and low individual responsiveness (0.8%). This change was paralleled by a very likely increase in Hb mass (2.8%) (24). Levine & Stray-Gundersen failed to find any effect on performance after 4 weeks of Hi-Hi intervention despite an increase of $\dot{V}O_{2max}$ (3.4%) and red cell mass (10%) (9). Burtscher et al. studied two groups of amateur runners and found no group differences in cycling total work capacity between the Hi-Hi group and the Lo-Lo controls: 3 and 16 days after the intervention the Lo-Lo group improved 8% and 17% whereas the Hi-Hi group improved 0.3% and 8%, respectively (25).

Only Rodríguez et al. showed a significant improvement in swimming performance after living and training at 2320 m during 3 or 4 weeks (e.g., 3.1% and 3.4% in specific 100 m or 200-m time trial), but this change was not significantly different from that experienced by the Lo-Lo control group (3.7%) (26). Interestingly, two studies reporting increases in $\dot{V}O_{2max}$ did not find a concomitant improvement in performance compared with SL controls. In summary, only one study actually provided evidence of superior improvement of Hi-Hi altitude training compared with SL (24). However, the magnitude of these changes seems lower than can be expected because of a SL training camp, and placebo or nocebo effects cannot be ruled out.

Hi-Lo and Hi-HiLo controlled studies

Four controlled studies were identified (table 2). Levine & Stray-Gundersen were the first to use the Hi-Lo strategy in their classical study cited above (9), in which they assigned collegiate and club amateur runners to Hi-Hi, Hi-Lo, and Lo-Lo (control) groups. They reported an improvement on 5000-m running performance (1.3%) in the Hi-Lo runners three weeks after the training camp and attributed this to increased $\dot{V}O_{2max}$ (5%) and red cell mass (10%), according to the "erythropoietic paradigm". In a study by Dehnert et al. two groups of subelite triathletes followed a Lo-Lo or Hi-Lo intervention for 2 weeks and found no effects on cycling or treadmill running performance despite a 7% increase in $\dot{V}O_{2max}$ and unchanged Hb mass (27). In contrast, Wehrlin et al. (20) studied a group of 10 elite orienteers using a Hi-Lo strategy for 24 days and comparing them with 7 Lo-Lo cross country skiers, and reported an improvement in 5000-m running performance (1.6%) in the Hi-Lo group, paralleled by increased $\dot{V}O_{2max}$ (4.1%) and red cell mass (5.3%), which are comparable to previous results in runners (9). Finally, Rodríguez et al. conducted the only controlled study using the Hi-HiLo strategy in which athletes live at altitude and train at the same and a lower altitude (26). Four groups of international level swimmers were compared: Hi-Hi for 3 and 4 weeks (previously cited), and Hi-HiLo and Lo-Lo controls for 4 weeks. Although all groups improved after a well-controlled training camp, the Hi-HiLo group of swimmers further improved 50-, 100- (sprinters) or 200- (non-sprinters), and 400-m swimming performance (5.5%, 6.3% and 4.7%, respectively) 2 to 4 weeks after the training camp. However, this substantial improvement in performance could not be attributed to changes in $\dot{V}O_{2max}$, Hb mass or swimming economy and, therefore, to the "erythropoietic paradigm".

Classical altitude training (Hi-Hi) uncontrolled studies

Nine uncontrolled studies using the classical Hi-Hi strategy met the inclusion criteria (table 3). Overall, only 2 studies showed some evidence of beneficial effects on performance (28, 29) and 1 was uncertain (30). Noteworthy, in the study by Roels et al. the modest increase in 2000-m trial (1.9%) was only significant when the swimmers lived and trained at 1200 m of altitude, but not at 1850 m (29). Moreover, another study showed a decrease in performance after 21 to 27 days of Hi-Hi intervention in four different groups (n = 97) of elite swimmers (31). The other 6 studies did not show significant changes in performance despite some modest changes in $\dot{V}O_{2max}$ (32, 33), Hb mass (31, 34), blood red cell markers (30, 35) or without haematological changes (36).

Hi-Lo and Hi-HiLo uncontrolled studies

The systematic review included 3 uncontrolled studies examining the Hi-Lo strategy and 3 studies using the Hi-HiLo strategy (table 4). These studies were conducted by mostly the same group of researchers and used similar designs and methodologies. In a retrospective study using the Hi-Lo approach, 8 out of 12 collegiate runners were classified as responders and improved their time in a 5000-m time trial by 3.6% whereas the non-responder decreased their performance time by 1.3%. The better times of the responders was paralleled by a non-significant increase in $\dot{V}O_{2max}$ (7.5%) (37). Coincident results were obtained by these authors in a prospective study with elite distance runners (37). Also Stray-Gundersen et al. reported modest but significant performance gains in 22 elite runners on a 3000-m time trial (1.1%) associated to a 3% increase in $\dot{V}O_{2max}$ (18). To identify the optimal altitude for training using the Hi-HiLo approach, Chapman et al. compared four groups of collegiate runners living at four altitudes (from 1780 to 2800 m) and training at varying altitudes from 1250 to 3000 m. They found that only the middle altitudes (i.e., 2084 and 2454 m) evoked significant gains in 3000-m time trial running performance (2.1 to 2.8%), associated to a 3% to 8% increase in $\dot{V}O_{2max}$ (38). Similarly, Saugy et al. conducted a study with 13 well-trained triathletes who lived at 220 m and trained at 1100-1200 m of altitude and found an improvement in 3000-m time trial running performance (3.3%) after 3 weeks upon return to sea level, with no changes 1 and 7 days after the altitude training camp. $\dot{V}O_{2max}$ also increased by 5.2% (39).

Study	Subjects (level)	Strategy[a]	Sample size[b]	Design[c]	Follow up[d]	Training	
						Altitude (m)	Duration (d)
Adams et al. 1975 (23)	Runners (middle-distance)	Lo-Lo vs. Hi-Hi	12M	CON X-over	D1-3	16 2300	20 20
Burtscher et al. 1996 (25)	Runners (amateur)	Lo-Lo vs. Hi-Hi	12M 10M	CON R Pre-post	D3,16	187 2315	12
Levine & Stray-Gundersen 1997 (9)	Runners (collegiate/ club level)	Lo-Lo vs. Hi-Hi	9M, 4F 9M, 4F	CON R Pre-post	D15,43, 71	150 2500-2700	28 28
McLean et al. 2013 (24)	Australian footballers (elite)	Lo-Lo vs. Hi-Hi	9M 21M	CON Pre-post NR	D1,30	30 ~2130	19 19
Rodríguez et al. 2015 (26)	Swimmers (elite)	Lo-Lo vs. Hi-Hi Hi-Hi	8F, 3M 8F, 7M 10F, 6M	CON NR Pre-post	D1,8,15,21,28	190 or 655 2320 2320	28 21 28

Table 1. Summary of CONTROLLED studies on natural altitude training using the Hi-Hi strategy for sea level performance enhancement.

[a] Lo-Lo, live low–train low; Hi-Hi, live high–train high.
[b] F, females; M, males.
[c] CON, controlled trial; UN, uncontrolled trial; R, randomised; NR, non-randomised; X-over, cross-over
[d] D#, testing post-intervention (day number).
[e] TT, time trial in specific sport; CY, cycling test; TWC, total work capacity; TM, treadmill test.
[f] RCM, red cell mass; RCV, red cell volume.
↑, improvement/increase/benefit; <—>, no change; ↓, worsening/decrease/harm; =, same as above
*, significantly different from values measured before training or compared to sea-level controls ($p<0.05$); n.s., non-significant difference ($p\geq0.05$); ?, uncertain/not reported.

Phase	Effects on performance measures[e] (Δ% from pre-values)	Other changes $\dot{V}O_{2max}$	Hb_{mass}	Other[f]
?	TT 2mi: ↑1.3% (n.s. vs. SL)	↓2.8%	?	?
?	CY TWC: ↑8% at D3, ↑17% at D16 ↔0.3% at D3, ↑8% at D16 (n.s. between groups)	↑10% at D16	?	?
?	↔ ↔	↔ ↑3.4%*		RCM ↔ ↑10%*
Pre-Seasor	TT 2km: Post1: ↑1.5%* (±4.8% 90%CL) Post2: trivial changes vs. Post1	?	Hi-Hi: Post1 2.8%* Post2 ↔	?
In-season	TT 50, 100/200, 400m: ↑3.2%, 3.7%, 1.6%* ↑3.4%, 3.1%, 0.6%* ↑3.7%, 3.4%, 3.3%*	↔ ↔ ↔	↔ ↑3.8%* ↑6.2%*	Economy↔ ↔ ↔

Study	Subjects (level)	Strategy[a]	Sample size[b]	Design[c]	Follow up[d]	Training	
						Altitude (m)	Duration (d)
Levine & Stray-Gundersen 1997 (9)	Runners (collegiate/ club level)	Lo-Lo vs. Hi-Lo	9M, 4F 9M, 4F	CON R Pre-post	D15,43, 71	150 L 2500, T 1250	28 28
Dehnert et al. 2002 (27)	Triathletes (subelite)	Lo-Lo vs. Hi-Lo	8M, 3F 7M, 3F	CON R Pre-post	D7,14	800 L 1956, T 800	14
Wehrlin 2006 (20)	Orienteers and cross country skiers (elite)	Lo-Lo vs. Hi-Lo	3M, 4F 5M, 5F	CON NR Pre-Post	D10	500-1600 L 2500, T 1000-1800	24 24
Rodríguez et al. 2015 (26)	Swimmers (elite)	Lo-Lo vs. Hi-HiLo	8F, 3M 4F, 8M	CON NR Pre-post	D1,8,15, 21,28	190 or 655 L/T 2320, T 690	28 28

Table 2. Summary of CONTROLLED studies on natural altitude training using the Hi-Lo or Hi-HiLo strategies for sea level performance enhancement.

[a] Lo-Lo, living low, training low; Hi-Lo, live high–train low; Hi-HiLo, live high–train high and low; L, living; T, training.

[b] F, females; M, males. -over, crossover; R, randomised; NR, non-randomised.

[d] D#, testing post-intervention (day number).

[e] TT, time trial in specific sport; CY, cycling test; TM, treadmill test.

[f] RCM, red cell mass; RCV, red cell volume.

↑, improvement/increase/benefit; <—>, no change; ↓, worsening/decrease/ harm; =, same as above

*, significantly different from values measured before training or compared to sea-level controls (p<0.05); n.s., non-significant difference (p≥0.05); ?, uncertain/not reported.

	Effects on performance measures[e] (Δ% from pre-values)	Other changes		
Phase		V̇O$_{2max}$	Hb$_{mass}$	Other[f]
?	↔ TT 5km ↑1.3%*	↔ ↑5%*		RCM ↔ ↑5.3%*
?	↔ ↔ Incremental CY ramp, ↔ TM tests, n.s. trend to improve running time	↔ ↑7%	↔ ↔	? ?
Pre-season	No measures in Lo-Lo group TT 5km ↑1.6%	? ↑4.1%	↔ ↑5.3%	
In-season	TT 50, 100/200, 400m: ↑3.2%*, 3.7%*, 1.6%* ↑5.5%*, 6.3%*, 4.7%* (Hi-HiLo > Lo-Lo*)	↔ ↔	↔ ↑1.3%	↔ Economy ↔ Economy

Study	Subjects	Strategy[a]	Sample ze[b]	Design[c]	Follow	Training Altitude
Faulkner et al. 1967 (35)	Swimmers, fit men	Hi-Hi	16M 5M	UN Pre-post	D1	2300
Faulkner et al. 1968 (32)	Runners (subelite)	Hi-Hi	5M 5M 4M	UN Pre-post	D4 to D13	2300 2300-3100 4300-2300
Mizuno et al. 1990 (28)	X-country skiers (subelite)	Hi-Hi	10M	UN Pre-post	?	2100 2700
Roels et al. 2006 (29)	Swimmers (elite)	Hi-Hi Hi-Hi	9M	UN X-over	D1,3,15,17	1200 1850
Schmitt et al. 2006 (33)	X-country skiers, swimmers, runners (elite)	Hi-Hi	20M	UN Pre-post	D1,15	1200
Hue et al. 2007 (36)	Swimmers, (regional/ interregional)	Hi-Hi	2F, 6M	UN Pre-post	D10,30	1800
Siewierski et al. 2012 (30)	Swimmers (elite)	Hi-Hi	6M, 2F	UN Pre-post	Race results pre-post	2300
Gough et al. 2012 (34)	Swimmers (elite)	Hi-Hi	14M, 3F	UN Pre-post	D1,7,14,28	2135-2323
Wachsmuth et al. 2013 (31)	Swimmers (elite)	Hi-Hi1 Hi-Hi2 Hi-Hi3 Hi-Hi4	13M, 6F 6M, 4F 5M, 2F 4M, 7F	UN Pre-post	All racing results	2320 2320 2320 1360

Table 3. Summary of UNCONTROLLED studies on natural altitude training us

[a] Lo-Lo, living low, training low; Hi-Hi, live high–train high; L, living; T, training.
[b] F, females; M, males.
[c] CON, controlled trial (vs. sea level); UN, uncontrolled trial (vs. sea level); X-over, crossover; R, randomised; NR, non-randomised.
[d] D#, testing post-intervention (day number).
[e] TT, time trial in specific sport; CY, cycling test; PPO, peak power output; TM, treadmill test; Re, responders; NRe, non-responders; pts, FINA score points.

		Effects on performance measures (Δ% from pre-values)[e]	**Other changes**		
Duration	**Phase**		**$\dot{V}O_{2max}$**	**Hb_{mass}**	**Other[f]**
23 14	?	↔Tethered swimming 100, 200, 500 yd	↔	↔	Hb↑10%* Htc↑4%*
42 35 38	?	?↑TT 1mi 1.2% ?↑TT 2mi -0.5% ?↑TT 3mi 2.3%	↑2%	↑2%	?
14 14	?	TM running time to exhaustion ↑17%*	↔	?	↑29 O_2 deficit ↑6% buffer capacity
13 13	?	TT 2km: ↑1.9%* ↔	↔ ↔	↔ ↔	RBC: ↔ ↔
18	Balanced training load	↔CY PPO 1.9%	↑3.3%*		↑economy 7%*
8	Competitive period	↔	?	?	?
23	Competitive period	?↑ 3.1% pts	?	?	RBC: ↑14.4% Hb: ↑13.5% Htc: ↑14.8%
21	?	↔	?	↑4%*	
27 26 21 23	Two years preparation for Olympic Games	D0-14 ↓11 pts D15-24 ↓4 pts D25-35 ↓2 pts	?	↑6.5% ↑7.2% ↑8.6% ↑3.8% ↑3%M, 2,7%F	?

[f] RCM, red cell mass; RCV, red cell volume.
↑, improvement/increase/benefit; <—>, no change; ↓, worsening/decrease/harm; =, same as above
*, significantly different from values measured before training or compared to sea-level controls ($p<0.05$); n.s., non-significant difference ($p\geq0.05$); ?, uncertain/not reported.

Study	Subjects (level)	Strategy[a]	Sample size[b]	Design[c]	Follow up[d]	Training	
						Altitude (m)	Duration (d)
Chapman et al. 1998 (retrospective) (37)	Runners (collegiate)	Hi-Lo	4F, 9M	UN Pre-post	D3	L 2500 T 1200-1400	28
Chapman et al. 1998 (prospective) (37)	Distance runners (elite)	Hi-HiLo	8M, 14M	UN Pre-post	D3	L 2500 T 1200-1400	20
Stray-Gundersen et al. 2001 (18)	Runners (elite)	Hi-HiLo	8F, 14M	UN Pre-post	D3	L 2500 T 1250	27
Chapman et al. 2013 (38)	Distance runners (collegiate)	Hi-HiLo Hi-HiLo Hi-HiLo Hi-HiLo	4F, 6M 4F, 7M 4F, 8M 4F, 8M	UN Pre-post	D1,14	L 1780 L 2084 L 2454 L 2800 (T 1250-3000)	28
Saugy et al. 2014 (39)	Triathletes (well trained)	Hi-Lo	13M	UN Pre-post	D1,7,21	L 2250 (T 1100-1200)	18

Table 4. Summary of UNCONTROLLED studies on natural altitude training using the Hi-Lo or Hi-HiLo strategies for sea level performance enhancement.

[a] Lo-Lo, living low, training low; Hi-Hi, live high–train high; L, living; T, training.
[b] F, females; M, males.
[c] CON, controlled trial (vs. sea level); UN, uncontrolled trial (vs. sea level); X-over, crossover; R, randomised; NR, non-randomised.
[d] D#, testing post-intervention (day number).
[e] TT, time trial in specific sport; CY, cycling test; PPO, peak power output; TM, treadmill test; Re, responders; NR, non-responders; FINA pts, FINA score points.
[f] RCM, red cell mass; RCV, red cell volume.
↑, improvement/increase/benefit; <—>, no change; ↓, worsening/decrease/harm; =, same as above

	Effects on performance measures (Δ% from pre-values)*	**Other changes**		
Phase		**VO_{2max}**	**Hb_{mass}**	**Other**
?	R (n=8) ↑ TT 5km 3.6*% NR (n=4) ?↓ TT 5km -1.3%	R ↑7.5%* NR ↔	?	Hb: R ↑ 9.5* NR ↑8.0* Htc: R↑5.9* NR ↑7.9*
?	R (n=9) ↑ TT 3km -5.8s* NR (n=5) ↔ TT 3km	R ↑3.4 ml/kg·min NR ↔ (n.s.)		
Near season's fitness peak	TT 3 km: ↑1.1%*	↑3%		↑1 g/dl
?	TT 3 km: ↔ ↑ 2.1%*D1, 2.2%*D14 ↑ 2.8%*D1, 2.1%*D14 ↔	↑2% D1, 4%* D14 ↑3%* D1, 5%* D14 ↑4%* D1, 8%* D14 ↑6%* D1, 4%* D14	? ? ? ?	RCM: ↑7.0% ↑6.3% ↑6.2% ↑6.3%
Competitive season	TT 3 km: ↔ at D1, D7 ↑ 3.3%* at D21	↑5.2%	↑1.8%	PPO: ↑6.6%

*, significantly different from values measured before training or compared to sea-level controls ($p<0.05$); n.s., non-significant difference ($p\geq0.05$); ?, uncertain/not reported.

Discussion

This systematic review, which aimed at assessing the empirical evidence sustaining the use of AT in athletes with focus on SL performance enhancement, does not appear sufficiently robust to determine the efficacy and appropriate characteristics (duration, altitude and training requirements) of an AT camp. Neither it can conclude which of the natural AT strategies is best for enhancing performance at SL. The reviewed studies are difficult to compare with each other directly, given the many differences in experimental design, type of participants, outcome measures and methodology. Notwithstanding, there seems to be a certain consensus—perhaps lacking compelling evidence to support it—that when athletes are exposed to a high enough altitude, for a long enough amount of time, and are able to preserve fitness by training hard under both hypoxic and normoxic conditions, the majority may improve physical performance (40).

We have reviewed publications from 1967 to 2017, a 50-year period. A total of 20 studies have been appraised, but only 7 published articles (33%) had a controlled design. The remaining 14 studies (67%) were uncontrolled and provide low quality evidence since performance changes can be attributed to training alone, training camp effect or placebo/nocebo effect. Concerning the 5 controlled Hi-Hi studies, only the one published by MacLean et al. (24) provided limited evidence of superior improvement compared with SL controls, although the high interindividual variability (-3.3–6.3%) argues against a real AT effect and placebo/nocebo effects cannot be ruled out.

In the last decade the Hi-Lo approach has gained interest over the classical Hi-Hi strategy in the scientific literature and among many endurance athletes (4). In our review, the results of the 4 controlled Hi-Lo or Hi-HiLo studies seem somewhat more convincing compared with those using the classical Hi-Hi approach. In their milestone study, Levine & Stray-Gundersen showed that the Hi-Lo strategy evoked an increase in 5000-m time trial performance (1.3%) in collegiate and club runners (9), despite some researchers argue that this modest improvement could be attributed to a placebo or nocebo effect, as another Hi-Hi group showed the same improvement in $\dot{V}O_{2max}$ and red cell mass without any change in performance (1). Similar limitations can be attributed to the study by Wehrlin et al. since the improved 5000-m running performance (1.6%) lacked of concomitant performance measures in the control group (20). A recent investigation was the first to show substantial performance improvements after a terrestrial Hi-HiLo intervention using a controlled design (26). This investigation showed that SL swimming performance of elite swimmers in 100- (sprinters) or 200-m (non-sprinters) time trials was not altered, or in some cases impaired immediately, but improved significantly by ~3.1–3.7% after 1 to 4 weeks of recovery following completion of a coach-prescribed training camp, whether it was conducted at SL or at moderate altitude (2320 m). By including 2 weekly sessions of high-intensity training at lower altitude (Hi-HiLo strategy) a greater improvement in performance occurred 2 and 4 weeks after the training camp (5.3% and 6.3%, respectively). Similarly, further gains in 400- and 50-m freestyle time trial performance was noted 2 weeks (4.2% and 5.2%, respectively) and 4 weeks (4.7% and 5.5%, respectively) following return to SL. In addition, this study shows that the delayed performance improvements are not linked to changes in $\dot{V}O_{2max}$, oxygen kinetics or Hb mass and hence cannot be attributed exclusively to an enhanced systemic oxygen transport capacity.

Globally, these results are in line with estimations published in a meta-analytic review by Bonetti & Hopkins, who concluded that "performance changes in studies using the conventional Hi-Hi approach were unclear, whereas changes using the terrestrial Hi-Lo strategy were considered likely to be effective both for elite and subelite athletes (~4%), or a more realistic 1.5% when performance was predicted from uncontrolled studies" (7). These estimations are in line with a recent review by Saunders et al. (5) in which, by using a regression analysis of average performance changes, it was estimated that a 3-week terrestrial AT camp would elicit mean performance improvements of ~1.8% (Hi-Hi) and ~2.5% (Hi-Lo) (5).

Levine and Stray-Gundersen were the first to test the hypothesis that acclimatization to moderate altitude (2500 m) plus training at low altitude (1250 m) (Hi-Lo paradigm) improves SL performance in well-trained runners more than in equivalent SL or Hi-Hi controls (9). They also concluded that the correlation between the increase in $\dot{V}O_{2max}$ and the improvement in 5000-m time after the field training camp argues strongly that this is a key adaptation during altitude training and a necessary mechanism for improving SL performance. Despite this, the performance gain was only 1.3% from pre-training values. Notwithstanding, this study changed the previous AT paradigm that was only focussed on the classical Hi-Hi strategy.

Concerning the 9 uncontrolled Hi-Hi studies included in this review, we can see a very similar picture as for the controlled studies, since only two studies showed some beneficial effects on performance (28, 29), one was uncertain (30), and 1 even showed impaired performance after in a very large number of elite swimmers (31).

Among the uncontrolled Hi-Lo or Hi-HiLo investigations, two (37) should be analysed with caution as the participants, collegiate or elite runners, were categorized post-facto into 'responders' and 'non-responders', as they aimed at investigating the individual variation in response to AT. The other 2 studies showed performance changes similar to the controlled groups, although the risk of placebo or nocebo effects is exacerbated. Interestingly, moderate altitudes of ~2100-2500 m were identified as optimal for benefits in 3000-m running performance (41).

Conclusions

There are several limitations in every study design using terrestrial AT, including the impossibility of blinding the intervention, limitations in recruiting large numbers of participants, difficulties in group randomisation, control of placebo and nocebo effects, large variability in the response, etc. These barriers make difficult the comparison of the existing studies and the design of new investigations that can meet the high standards of scientific research.

Contrary to common expectations, the systematic review of 20 articles published along 50 years (1967 to 2017) shows that the quality of the empirical evidence about using natural altitude training in competitive athletes with the main goal of improving sea level performance is far from being compelling. However, the available evidence supports the concept that the Hi-Lo and Hi-HiLo strategies offer the best potential for performance benefits, as at least two controlled studies provided sound evidence of positive effects on performance in collegiate/club runners and elite swimmers, respectively. Uncontrolled studies also support this concept despite the lower quality of the evidence.

References

1. Lundby C, Millet GP, Calbet JA, Bartsch P, Subudhi AW. Does 'altitude training' increase exercise performance in elite athletes? Br J Sports Med. 2012;46(11):792-5.
2. Jacobs RA. Con: Live high-train low does not improve sea-level performance beyond that achieved with the equivalent living and training at sea level. High Alt Med Biol. 2013;14(4):328-30.
3. Hahn AG, Gore CJ, Martin DT, Ashenden MJ, Roberts AD, Logan PA. An evaluation of the concept of living at moderate altitude and training at sea level. Comp Biochem Physiol A Mol Integr Physiol. 2001;128(4):777-89.
4. Wilber RL. Application of altitude/hypoxic training by elite athletes. Med Sci Sports Exerc. 2007;39(9):1610-24.
5. Saunders PU, Pyne DB, Gore CJ. Endurance training at altitude. High Alt

Med Biol. 2009;10(2):135-48.
6. Rodríguez FA. Training at real and simulated altitude in swimming: too high expectations? In: Kjendlie P-L, Stallman RK, Cabri J, editors. Biomechanics and Medicine in Swimming XI. Oslo: Norwegian School of Sport Science; 2010. p. 30-2.
7. Armstrong LE, Johnson EC, Ganio MS, Judelson DA, Vingren JL, Kupchak BR, et al. Effective body water and body mass changes during summer ultra-endurance road cycling. J Sports Sci. 2015;33(2):125-35.
8. Levine BD, Stray-Gundersen J. Dose-response of altitude training: how much altitude is enough? Adv Exp Med Biol. 2006;588:233-47. Epub 2006/11/09.
9. Levine BD, Stray-Gundersen J. "Living high-training low": effect of moderate-altitude acclimatization with low-altitude training on performance. J Appl Physiol. 1997;83(1):102-12.
10. Levine BD, Stray-Gundersen J. Point: positive effects of intermittent hypoxia (live high:train low) on exercise performance are mediated primarily by augmented red cell volume. J Appl Physiol. 2005;99(5):2053-5.
11. Gore CJ, Hopkins WG. Counterpoint: positive effects of intermittent hypoxia (live high:train low) on exercise performance are not mediated primarily by augmented red cell volume. J Appl Physiol. 2005;99(5):2055-7; discussion 7-8.
12. Gore CJ, Clark SA, Saunders PU. Nonhematological mechanisms of improved sea-level performance after hypoxic exposure. Med Sci Sports Exerc. 2007;39(9):1600-9.
13. Fukuda T, Maegawa T, Matsumoto A, Komatsu Y, Nakajima T, Nagai R, et al. Effects of acute hypoxia at moderate altitude on stroke volume and cardiac output during exercise. Int Heart J. 2010;51(3):170-5.
14. Mazzeo RS. Altitude, exercise and immune function. Exerc Immunol Rev. 2005;11:6-16.
15. Stray-Gundersen J, Alexander C, Hochstein A, Lemos D, Levine BD. Failure of red cell volume to increase with altitude exposure in iron deficient runners. Med Sci Sport Exerc. 1992;24(5):S90.
16. Young AJ. Energy substrate utilization during exercise in extreme environments. Exerc Sport Sci Rev. 1990;18:65-117.
17. McGinnis G, Kliszczewiscz B, Barberio M, Ballmann C, Peters B, Slivka D, et al. Acute hypoxia and exercise-induced blood oxidative stress. Int J Sport Nutr Exerc Metab. 2014;24(6):684-93.
18. Stray-Gundersen J, Chapman RF, Levine BD. "Living high-training low" altitude training improves sea level performance in male and female elite runners. J Appl Physiol (1985). 2001;91(3):1113-20.
19. Stray-Gundersen J, Levine BD. Live high, train low at natural altitude. Scand J Med Sci Sports. 2008;18 Suppl 1:21-8.
20. Wehrlin JP, Zuest P, Hallen J, Marti B. Live high-train low for 24 days increases hemoglobin mass and red cell volume in elite endurance athletes. J Appl Physiol. 2006;100(6):1938-45.
21. Jones AM, Haramizu S, Ranchordas M, Burke L, Stear S, Castell LM. A-Z of nutritional supplements: dietary supplements, sports nutrition foods and ergogenic aids for health and performance--Part 27. Br J Sports Med.

2011;45(15):1246-8.
22. Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gotzsche PC, Ioannidis JP, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. PLoS medicine. 2009;6(7):e1000100.
23. Adams WC, Bernauer EM, Dill DB, Bomar JB, Jr. Effects of equivalent sea-level and altitude training on VO2max and running performance. J Appl Physiol. 1975;39(2):262-6.
24. McLean BD, Gore CJ, Kemp J. Application of 'Live Low-Train High' for Enhancing Normoxic Exercise Performance in Team Sport Athletes. Sports Med. 2014. Epub 2014/05/23.
25. Burtscher M, Nachbauer W, Baumgartl P, Philadelphy M. Benefits of training at moderate altitude versus sea level training in amateur runners. Eur J Appl Physiol. 1996(74):558-63.
26. Rodriguez FA, Iglesias X, Feriche B, Calderon-Soto C, Chaverri D, Wachsmuth NB, et al. Altitude training in elite swimmers for sea level performance (Altitude Project). Med Sci Sports Exerc. 2015;47(9):1965-78.
27. Dehnert C, Hutler M, Liu Y, Menold E, Netzer C, Schick R, et al. Erythropoiesis and performance after two weeks of living high and training low in well trained triathletes. Int J Sports Med. 2002;23(8):561-6.
28. Mizuno M, Juel C, Bro-Rasmussen T, Mygind E, Schibye B, Rasmussen B, et al. Limb skeletal muscle adaptation in athletes after training at altitude. J Appl Physiol (1985). 1990;68(2):496-502.
29. Roels B, Hellard P, Schmitt L, Robach P, Richalet JP, Millet GP. Is it more effective for highly trained swimmers to live and train at 1200 m than at 1850 m in terms of performance and haematological benefits? Br J Sports Med. 2006;40(2):e4.
30. Siewierski M, Słomiński P, Białecki R, Adamczyk J. Athletic performance of swimmers after altitude training (2,300 m above sea level) in view of their blood morphology changes. Biol Sport. 2012;29(2).
31. Wachsmuth NB, Volzke C, Prommer N, Schmidt-Trucksass A, Frese F, Spahl O, et al. The effects of classic altitude training on hemoglobin mass in swimmers. Eur J Appl Physiol. 2013;113(5):1199-211.
32. Faulkner JA, Kollias J, Favour CB, Buskirk ER, Balke B. Maximum aerobic capacity and running performance at altitude. J Appl Physiol. 1968;24(5):685-91.
33. Schmitt L, Millet G, Robach P, Nicolet G, Brugniaux JV, Fouillot JP, et al. Influence of "living high-training low" on aerobic performance and economy of work in elite athletes. Eur J Appl Physiol. 2006;97(5):627-36.
34. Gough CE, Saunders PU, Fowlie J, Savage B, Pyne DB, Anson JM, et al. Influence of altitude training modality on performance and total haemoglobin mass in elite swimmers. Eur J Appl Physiol. 2012;112(9):3275-85. Epub 2012/01/12.
35. Faulkner JA, Daniels JT, Balke B. Effects of training at moderate altitude on physical performance capacity. J Appl Physiol. 1967;23(1):85-9.
36. Hue O, Antoine-Jonville S, Sara F. The effect of 8 days of training in tropical environment on performance in neutral climate in swimmers. Int J Sports Med. 2007;28(1):48-52.

37. Chapman RF, Stray-Gundersen J, Levine BD. Individual variation in response to altitude training. J Appl Physiol. 1998;85(4):1448-56.
38. Chapman RF, Karlsen T, Resaland GK, Ge RL, Harber MP, Witkowski S, et al. Defining the "dose" of altitude training: how high to live for optimal sea level performance enhancement. J Appl Physiol (1985). 2013.
39. Saugy JJ, Schmitt L, Cejuela R, Faiss R, Hauser A, Wehrlin JP, et al. Comparison of "live high-train low" in normobaric versus hypobaric hypoxia. PLoS One. 2014;9(12):e114418.
40. Wilber RL. Introduction to altitude/hypoxic training symposium. Med Sci Sports Exerc. 2007;39(9):1587-9.
41. Rehrer NJ, Brouns F, Beckers EJ, Frey WO, Villiger B, Riddoch CJ, et al. Physiological changes and gastro-intestinal symptoms as a result of ultra-endurance running. Eur J Appl Physiol Occup Physiol. 1992;64(1):1-8.

Dietary nitrate effects in human athletic performance

Maria Silva[1] and Mónica Sousa[2]

Introduction

The field of sports nutrition has been studied for more than 50 years. It keeps growing fast, bringing new strategies to enhance athletic performance, to prepare for competition and to recover from exercise (1). Indeed, there are some supplements and sports foods proved to boost performance and recovery; nitrates (NO_3-) seem to be one of them and they are growing in popularity among athletes (1). These anions have been studied for the past few years to understand their effects in athletic performance.

According to Bailey SJ (1) and Lansley KE (2) NO_3- supplementation, either as beetroot juice or sodium nitrate, has benefits to cardiovascular health, reducing blood pressure, enhancing blood flow and increasing the driving pressure of oxygen to exercising tissue. Due to these reasons, it is believed that NO_3- could increase exercise performance (1). The effects of NO_3- seem to be mediated via reduction to nitrite (NO_2-) and then to nitric oxide (3-5). In fact, NO has been linked to vasodilatation, angiogenesis, mitochondrial biological processes, glucose uptake and calcium pump (6). All these properties appear to be very important in what respects sports, namely exercise efficiency and exercise performance (6).

Until recently, it was believed that NO was generated solely from L-arginine by an enzyme called NO synthase (7), resulting in endogenous production of NO3- and NO_2-. However, now it is known that there are two pathways. So, NO can be produced from L-arginine and oxygen and, subsequently, be oxidized to NO_2- and NO3- or, alternatively, NO3- can be reduced to NO2- by xanthine oxidase and facultative anaerobic bacteria in the oral cavity, and NO2- can be further reduced to NO and other reactive nitrogen species (6). This process is described in Figure 1.

1. Faculty of Nutrition and Food Sciences, University of Porto, Portugal
2. Nutrition & Metabolism, NOVA Medical School, Faculdade de Ciências Médicas, Universidade NOVA de Lisboa, Portugal

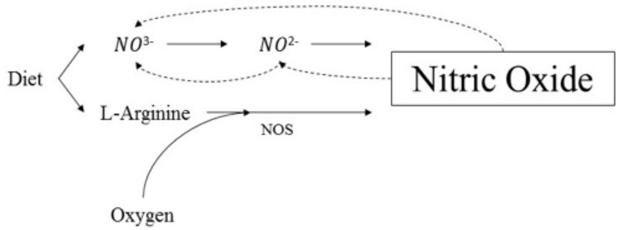


Figure 1 - Adapted from Jones AM., Dietary nitrate supplementation and exercise performance. Nitrate (NO_3-), nitrite (NO_2-) and NOS (NO synthase).

Baseline levels of NO_2- correlate positively with exercise performance in highly trained athletes independent of endothelial function (8). In fact, NO has been linked to vasodilatation, angiogenesis, mitochondrial respiration, mitochondrial biogenesis, glucose uptake and sarcoplasmic reticulum Ca_2+ handling (6). All these properties are relevant to athletic performance from fatigue resistance and exercise efficiency to exercise performance (6). However, potential benefits related to NO_3- supplementation have been a controversial question. In fact, there are several studies (9-11) which demonstrate that NO_3- may not have any benefits in exercise performance. Therefore, this review focuses on understanding the evidence-base of nitrate as an ergogenic supplement; on which mechanisms may be responsible for these ergogenic effects and to put forward some practical guidelines for a useful and safe use of nitrates.

Nitrate food sources

Although NO_3- exists in a range of vegetables (12) beetroot is the most popular. It has been already demonstrated that the NO_3- content present in this vegetable, in fact, gives rise to NO which has been showed to have benefits in exercise performance (6). Besides a high content of NO_3-, it is easy to deliver as a juice. Although it can be made at home, a commercial option is often the most convenient and palatable option. There are already many commercial options of beetroot juice. “BEET it” is one of the most known brand; BeetElite Neo shot, Love beets and Biotta also seem to be good options, as it is showed in Table 1.

	James white drinks beet it sport	James white drinks beet it organic beetroot juice 1 L	Love beets	Beet elite neo shot	Biotta beetroot juice
Per serving	70 ml	250 ml	414 ml	10 g	250 ml
Energy (Kcal)	72	103	160	30	110
Protein	2.5 g	2.3 g	2 g	0	2 g
Total carbohydrates	16 g	23 g	41 g	8 g	25 g
Of which sugars	16 g	22.5 g	30 g	7 g	24 g
Total fat	< 0,1 g	< 0,1 g	0	0 g	0 g
Fibre	< 0,5 g	< 0,5 g	2 g	0 g	1 g
Sodium	< 0,1 g	< 0,1 g	230 mg	15 mg	65 mg
Dietary nitrate	0.4 g	0.25 g	N.M.	0.4 g	N.M.

Table 1 - Beetroot juice: nutritional information

However, the consumption of foodstuffs with a reasonable content in the compounds responsible for the increment of NO has not been directly linked to an enhancement of sports performance. Some of these compounds might be L-arginine or L-citrulline which is a precursor of the first one. For example, 300 ml per day of watermelon juice (3.4 g L-citrulline per day) for 16 days have increased plasma concentration of L-arginine, L-citrulline and NO_2- (13). However, although systolic pressure was found to be higher in the group consuming watermelon juice compared with the control group, the time-to-exhaustion during a severe-intensity exercise test was not significantly different between groups (13). Nonetheless, the skeletal muscle oxygenation index during moderate-intensity exercise was better among individuals supplemented with watermelon juice (13). Moreover, other recent studies have shown that although the plasma antioxidant capacity was found higher in watermelon juice supplemented groups, there seems to be no influence on post-exercise inflammation and changes in innate immune function (14). Therefore, although watermelon juice supplementation can increase plasma NO_2- and improve muscle oxygenation during moderate-intensity exercise, it does not seem to improve exercise endurance or even to lower blood pressure in healthy adults (13).

Also, it is important to note that NO is synthetized from L-arginine by the nitric oxide synthase. L-arginine is considered a semi-essential amino acid because the body normally produces it in sufficient amounts.

According to Alvares et al. (3) physiological concentrations of L-arginine in healthy individuals are enough to saturate nitric oxide synthase (3) – L-arginine supplementation might not be useful. Meirelles and collaborators (15) also concluded that acute supplementation of L-arginine neither affects strength performance nor NO production(15). Thus, if an athlete intends to use nitric oxide as an ergogenic supplement, it might be more efficient to use the anaerobic pathway: nitrates – nitrites – nitric oxide. Approximately 80% of NO_3- is derived from vegetable consumption fertilizer (12).

Dietary NO_3- is determined by the level of nitrate in the water supply, type of vegetables consumed, amount of vegetables consumed and level of NO_3- in the vegetables, including the NO_3- content of fertilizer (12). Nitrate is mainly found in cell vacuoles and is transported in the xylem, which carries water and nutrients from the roots to the leaves. This means that leaf crops such as cabbage, lettuce and spinach have fairly large NO_3- concentrations (16). The accumulation of NO_3- is subject of factors such as genotype, soil conditions, growth conditions and storage and transport conditions. So, the average NO_3- content of one type of vegetable can vary substantially, as reported in Table 2.

Vegetable types and varieties	**Nitrite**	**Nitrate**
	mg/100 g fresh weight	mg/100 g fresh weight
Root vegetables		
Carrot	0.002–0.023	92–195
Mustard leaf	0.012–0.064	70–95
Green vegetables		
Lettuce	0.008–0.215	12.3–267.8
Spinach	0–0.073	23.9–387.2
Cabbage		
Chinese cabbage	0–0.065	42.9–161.0
Bok choy	0.009–0.242	102.3–309.8
Cabbage	0–0.041	25.9–125.0
Cole	0.364–0.535	76.6–136.5
Melon		
Wax gourd	0.001–0.006	35.8–68.0
Cucumber	0–0.011	1.2–14.3
Nightshade		
Eggplant	0.007–0.049	25.0–42.4

Table 2 - Adapted from Norman J Hord in "Food sources of nitrates and nitrites: the physiologic context for potential health benefits".

So, NO_3- is consumed through the regular diet. In fact, median daily intake of dietary NO_3- in highly trained athletes is 106 mg (which is considered an ergogenic amount), although with a large inter-individual variation (17). Thus, increasing the intake of nitrate-rich vegetables in the diet, such as spinach, might be a great alternative strategy for NO_3- supplementation.

Nitrates Effects in Endurance Exercise

Following ingestion, NO_3- is converted to NO_2- by commensal facultative bacteria residing in crypts on the surface of the tongue (6). In conditions of low oxygen availability, NO_2- can be converted into NO, which is known to play a number of important roles in vascular and metabolic control (6). Dietary NO_3- supplementation increases plasma NO_2- concentration and reduces the oxygen cost of submaximal exercise and can, in some circumstances, enhance exercise tolerance (18). It seems that a single oral dose of 10mg/Kg of NO_3- acutely (in an individual with 60 Kg of body mass corresponds to ~9,5 mmol) reduces the VO_2 peak without compromising the maximal exercise performance (18).

Dietary NO_3- supplementation with beetroot juice has been studied over past years and there is still not many agreement regarding this practice. In 2011, the results of one study (2) suggested that acute dietary NO_3- supplementation with 6.2 mmol of NO_3- ingested 2.5 h before the event, improves cycling time trial performance in moderately trained cyclists. One year later this theory was refuted with one study (9) that showed that a single dose of beetroot juice with a higher content of NO_3- (140 ml – 8.7 mmol of NO_3-) 2.5 h before the event did not have any effect in male well-trained cyclists.

Longer-term use of NO_3- supplementation has also been studied. In one study (19) with dietary supplementation in the form of beetroot juice, a group of 12 trained males ingested 140 ml of beetroot juice per day (8 mmol/d NO_3-) or placebo, for six days. After supplementation, on day six, subjects performed 60 min of submaximal cycling followed by a 10-km time trial. Six days of NO_3- supplementation reduced VO_2 during submaximal exercise and improved time-trial performance in moderately trained cyclists. In the same year, it was published another study (20) which concluded that a high dose (8.4 mmol NO_3-) of beetroot juice, but not a moderate dose (4.2 mmol NO_3-), consumed 2 h before exercise, may had improve a 2000-m rowing performance in highly trained athletes.

The timing and dose of NO_3- supplementation is highly variable among studies. However, improvements in performance arising from an acute dose of NO_3- 75 – 150 min before exercise suggest that ergogenic effects occur in a short time frame (21). Intake of beetroot juice should be initiated within 90 min prior to exercise and at least 6 – 8 mmol of NO_3- is required in order to enhance endurance performance (22).

Nitrates Effects in Resistance Exercise

A variety of enzymes can catalyse the reduction of NO_2- to NO and it is known that this process is facilitated in conditions of ischemia, hypoxia and low pH (6).

As far as NO_3- effects in strength sports are concerned, there are further less studies. However, it is known that during exercise the skeletal muscle is under low partial pressure oxygen and pH conditions (6). It is known that nitrate-nitrite-nitric oxide pathway is greatly enhanced in hypoxia and acidosis (23). Therefore, it might be possible that the stimulation of the nitrate-nitrite-nitric oxide pathway may influence muscle function and exercise performance (6).

Notwithstanding, previous studies (24-28) have showed that NO can lower force production, via depressing force output during isometric contractions. In 2012, Fulford and collaborators (29) concluded that the ingestion of 0.5 L/day of beetroot juice (10.2 mmol of NO_3-) for fifteen days resulted in a reduction in the mean phosphocreatine (PCr) cost of exercise averaged. Nevertheless, increasing NO bioavailability by ingesting beetroot juice did not seem to be associated with a reduction of force-generating capability in skeletal muscle. Also, these investigators found that NO_3- supplementation reduces PCr cost of force production. In 2014, a research (30) showed that seven days of NO_3- supplementation (9.7 mmol per day) increased excitation-contraction coupling at low frequencies of stimulation and enhanced evoked explosive force production in untrained humans. However, voluntary force production was not affected.

Another study (31) aimed to investigate the effects of NO_3- supplementation on performance of bench press resistance until failure. The authors concluded that 70 ml of a shot of beetroot juice (BEET it Sport nitrate) containing 6.4 mmol/L or 400 mg of NO_3- improved the performance in this resistance training session. Also in 2016, a study (32) concluded that supplementation with a nitrate rich beetroot extract-based, which contained 3 g of concentrated beetroot extract and was fortified with 35.2 mg of dietary NO_3- (Advocare VO_2 Prime Performance Nutrition Bar), provided neuromuscular advantages during metabolically taxing resistance exercise. These results were consistent with other trials: Coggan and collaborators (33) concluded that acute dietary NO_3- intake (11.2 mmol NO_3- 2 h before the event) increased whole-body NO production and muscle speed and power of knee extension by, on average, 11 and 6%, respectively, in healthy men and women. Although relatively small, improvements of this magnitude might be significant in power-based sports for an elite athlete, even a 1% increase in performance ability can double chances of winning a particular event (34).

NO interacts with many different types of proteins, such as ryanodine receptors or guanylate cyclase (35). Ryanodine receptors are sarcoplasmic reticulum calcium-release channels whereas guanylate cyclase converts guanosine triphosphate to cyclic guanosine monophosphate (cGMP) (35). The general consequence of cGMP-mediated effects of NO is to improve mechanical and metabolic muscle power, similar to a transformation of slow-twitch to fast-twitch muscle, an effect also summarized as “slow-to-fast” shift (36). This may be the main reason for the ergogenic effects of NO_3- supplementation in resistance sports.

Also, in this type of exercise, supplementation protocols were highly variable across studies. Although more research is needed, consuming 5 – 9 mmol of NO_3- 2.5 – 3 h prior to an exercise bout seems to be a good strategy (37).

Nitrates Effects in Intermittent Exercise

Intermittent exercise is becoming very popular among those who want to lose body fat. Regular high intensity intermittent exercise increases aerobic and anaerobic fitness and brings out significant muscle adaptations (38). Also, it seems that intermittent exercise has strong acute and chronic positive effects on insulin sensitivity and fat loss (39). Fatigue development during this type of exercise is linked to the decline of phosphocreatine concentration in muscle; since NO_3- has been shown to lower the PCr cost of force production during high-intensity intermittent exercise (39). This finding suggests that NO_3- supplementation might improve performance during high-intensity interval training.

Wylie and collaborators (39) concluded that a 5-day supplementation with 8.2 mmol NO_3- 2.5 h prior to exercise improved performance during repeated bouts of short-duration maximal-intensity interspersed with short recovery periods, but not during longer duration intervals or when a longer recovery duration was applied. It might be possible that NO_3- supplementation has more performance enhancement in some particular types of intermittent exercise (39). On the other hand, Aucouturier and collaborators (40) concluded that NO_3- supplementation was linked to a better tolerance to supramaximal intensity intermittent exercise by increasing total red blood cells concentration in the working muscle in the absence of effects on contractile function.

Also in high-intensity interval training (HIIT), 490 ml of beetroot juice (28 mmol NO_3-) 30 h before the event improved the performance and seemed to be a very useful ergogenic aid for team sports players (41). Besides, during prolonged intermittent exercise, such as team sports, research shows that 140 ml of beetroot juice per day (12.8 mmol NO_3- per day) for seven days enhanced repeated sprint performance and attenuated the decline in cognitive function (reaction time, for example) (42). In national-level male kayak athletes, 4.8 mmol NO_3- improved exercise economy predominantly reliant on the aerobic energy system (43). Greater volumes of beetroot juice (9.6 mmol NO_3-) also resulted in enhancements of time trial performance in international-level female kayak athletes. Nyakayiru and collaborators concluded that 140 mL of beetroot juice (~800 mg nitrate/day) for six subsequent days improved high-intensity intermittent type exercise performance in trained soccer players (44). This 6-day beetroot juice protocol resulted in quantifiable improvements in high-intensity intermittent running performance and on the Yo-Yo IR1 test. During this test, mean heart rate was lower following beetroot juice ingestion than following nitrate-depleted beetroot juice treatment

CrossFit is a sport which includes a wide variety of functional high-intensity exercises. Performance in this sport is highly dependent on peak power and fatigue resistance (45). Therefore, NO_3- could be a useful ergogenic agent for CrossFit athletes. Kramer and colleagues concluded that six days of dietary NO_3- supplementation (8 mmol potassium NO_3- per day) in male CrossFit athletes improved the peak Wingate power 24 h following the final NO_3- dose; however, there were no improvements in 2-km rowing time-trials or CrossFit performance (46). Hence, further research is needed to stablish the best supplementation protocol. Notwithstanding, 8 mmol NO_3- 2 – 4 h prior to exercise seems to be a reasonable option to take advantage from to promote ergogenic effects by NO_3- .

Metabolic Adaptations

Dietary NO_3- has been linked to the reduction of oxygen cost of submaximal exercise (6). Besides, NO_3- supplementation seems to enhance performance and improve exercise tolerance in moderately trained individuals (47). It is essential to be aware that there are some variables that can affect the ergogenic benefits related to nitrate supplementation in elite athletes. Being an elite athlete demands a very intense exercise-training routine, which is connected with a much higher daily energy expenditure and, of course, with a greater daily energy intake in comparison with a non-trained subject (6). According to Porcelli (47) the optimal NO_3- loading required to increase NO in plasma and, consequently, to enhance performance in elite athletes is quite different from low-fit subjects - elite athletes need a higher dose to improve sports performance. This means that the individual fitness level seems to affect the benefits induced by dietary NO_3- supplementation. Additionally, if an athlete maintains a healthy food pattern, dietary NO_3- consumption is high (11). Maybe for that reason, the plasma NO_2- baseline is elevated in comparison with non-trained subjects. Alternatively, it has been concluded that baseline plasma NO_2- or NO_3- is higher in endurance-trained athletes compared to untrained individuals due to a greater nitric oxide synthase activity (48). These differences might reduce the NO_3- supplementation potential, altering the physiological responses to exercise in endurance athletes (11).

An elite athlete spends decades on intense exercise training. This induces reconditioning responses in the skeletal muscle vascularization and mitochondrial efficiency (49). To what skeletal muscle vascularization may concern, there is an increase in capillary density which is likely to reduce the chance of developing a hypoxic environment in the active muscle (49). Therefore, the pathway nitrate–nitrite–nitric oxide is compromised. Therefore, this pathway seems to have more relevance in sedentary individuals compared to elite athletes (11).

Another issue that is important to be aware is that an elite athlete is an elite in a specific sport. It is expected that in that specific sport, oxygen delivery does not restrict performance in a highly-trained athlete who does that every single day (49). Also, NO_3- supplementation seems to reach better results if exercise activities combine a higher relative oxygen consumption (%VO_2 maximum) with higher absolute workout (Kg/W). A greater dependency on fast-twitch muscle fibre recruitment and anaerobic energy supply can improve contractile function and increase performance (50). This suggests that endurance athletes, who typically have a low proportion of these fibres in their body, might not benefit of the physiological response to NO_3- supplementation (6).

Acute Supplementation versus Chronic Supplementation

Acute and chronic NO_3- supplementation have been used in plenty of studies with controversial conclusions. It is not yet known whether shorter or longer periods of supplementation have similar or different results. Webb et al. (51) assessed the effects of a single dose of beetroot juice (22.5 mmol of NO_3-) on plasma nitrite concentration and blood pressure over 24 h. Plasma NO_2- concentration reached its peak 3 h post-ingestion and remained close to this value for more 2 h. It returned to baseline after 24 h. The systolic and diastolic blood pressure decreased 2.5 – 3 h after the beetroot juice intake (51).

Larsen FJ et al. (52) used two periods of tree days separated by a washout interval of ten days. The daily dose of 0.1 mmol of NO_3-/Kg was divided and ingested three times daily. The results showed a lower oxygen demand during submaximal work and an increase in lactate concentration, indicating that energy production had become more efficient.

In 2010, Vanhatalo and collaborators showed that low (3 mmol) and moderate (6 mmol) amounts of NO_3- supplementation increased plasma NO_2- in a dose-dependent manner after 2 h, seven days and four weeks of supplementation. The same did not happen with the submaximal exercise oxygen uptake – a low dose did not have any effects either after 2 h, seven days or four weeks of supplementation. However, a moderate dose lowered this marker in all groups. Generally speaking, a reduction in submaximal exercise oxygen uptake can be achieved by ingesting 6 mmol NO_3- per day chronically with and without the acute ingestion of nitrates.

In athletes, acute beetroot consumption (6.2 mmol of NO_3-) seems to increase the mean power output and the power output to VO2 ratio and mitochondrial efficiency (53) and reduces blood pressure (54). These effects are maintained if supplementation is continued. Long-term NO_3- supplementation modulates muscle function through its role in the regulation of blood flow, glucose uptake, calcium homeostasis, mitochondrial respiration and biogenesis (6).

Although 15 days of NO_3- supplementation has been shown to improve exercise performance (37), most of recent investigations suggest that chronic NO_3- supplementation over seven days also has positive ergogenic effects (54).

For now, it seems that NO_3- supplementation may enhance exercise performance either after 2 – 3 h of supplementation or after seven or more days.

Are nitrates safe?

NO_3- and NO_2- can form N-nitrosamines which are potential carcinogens (37). In fact, in 2011 dietary N-compounds were associated with a higher gastrointestinal cancer incidence, specifically rectal cancer (55). Indeed, the Food and Drugs Administration (FDA) put restrictions to regulate nitrates and nitrites levels in both food and water within the US. However, in 2015, a study (56) showed that the presence of NO_2- in food is free of danger and a diet high in NO_3- had benefits for health. In turn, the European Food Safety Authority (EFSA) defends that no new data were identified that would require a revision of Adequate Dietary Intake (41) values – 0 – 3.7 mg NO_3-/Kg body weight and 0 – 0,07 mg NO_2-/Kg body weight (57).

While direct ingestion of NO_2- is potentially hazardous, the use of NO_3- from natural vegetable sources, such as beetroot juice, is of much less concern in terms of acute toxicity. In this case, only a minor part of the NO_3- is converted in vivo (58). The average increase of NO_2- concentration in saliva is 20 ppm/100 mg NO_3- ingested (59). Also, any possible harmful effect of nitrosation is inhibited by antioxidants which are also in those vegetables (6). Still, a potential risk of a deleterious effect exists if there is an inappropriately storage (58). Contamination of food or beverage by nitrate-reducing bacteria leads to NO_2- accumulation over time (58). However, the expert consensus refers that NO_3- supplementation with BJ is very unlikely to be harmful (6). Therefore, current data does not provide strong evidence supporting NO_3- restriction (37). Athletes should be advised to use vegetables sources if they intend to use dietary NO_3- supplementation as an ergogenic aid. Also, as far as kidney failure is concerned, 450 mg of potassium nitrate per day for seven days did not induce any detrimental effect in the kidney (60). Even so, it is not known if longer-term intake of high-nitrate vegetable products may be dangerous for health and further long-term studies are necessary.

Practical considerations for nitrate supplementation

Another question that it is important to be aware is that NO_3- is converted to NO_2- by commensal bacteria on the surface of the tongue (6) and that there are some factors that can affect these bacteria. Rising the mouth with the antibacterial mouthwash prior to the NO_3- supplementation has no effect on NO_3- accumulation in saliva or plasma but suppresses its conversion to NO_2- in saliva and attenuates the NO_2- plasma rise (61). This happens because the antibacterial mouthwash removes the commensal bacteria and constricts the NO-dependent biological effects of dietary NO_3-. This theory was confirmed by a study (62) which concluded that a twice daily use of an antibacterial mouthwash for three days decreased oral NO_3- reduction with a concomitant increase in systolic blood pressure. Regardless the fact that this might assure the safety of NO_3- supplementation, because nitrate in not converted to nitrite, it will inhibit any ergogenic potential of nitrate.

It is important to note that none of these studies were performed with children or adolescents. Further research in this population is needed to assess potential hazards linked to nitrate supplementation and possible ergogenic effects in young athletes. Also, the International Olympic Committee advises to encourage a dietary education, which should emphasize good eating patterns to support health and sports participation demands: a balanced intake of nutrition-dense carbohydrates, high-quality protein and sufficient dietary calcium, iron and vitamin D (63).

Another consideration should be taken in what respects the carbohydrate amounts in beetroot juice used in studies. When placebo refers to beetroot juice nitrate-depleted, conclusions are more trustworthy since the amount of carbohydrates (and other components, except for NO_3-) is the same in both groups (placebo and intervention). However, when placebo is water (64), the carbohydrate content of whole beetroot juice might induce a slightly more pronounced ergogenic effect (65). This carbohydrate amount should be considered in the pre-event meal carbohydrates calculation.

Conclusion

There is not yet a completely defined protocol for NO_3- amounts and intake times, but 6 – 8 mmol of NO_3- per day, ingested chronically (seven days) is a good option to enhance exercise performance. Also, the same amount ingested acutely, 2 h before the event, seems to result in an equivalent improvement of athletic performance.

Further research is necessary to assess potential hazards linked to NO_3- supplementation protocols longer than seven days. It is important to refer that the NO_3- ergogenic potential can, actually, be achieved through foodstuffs instead of supplements – increasing the intake of nitrate-rich vegetables, such as bok choy, rocket and cabbage (17). Dietary NO_3- supplementation through a diet rich in vegetables seems to result, in a similar way to supplementation, in a lower oxygen demand and in a greater efficiency of energy production (52).

Real conditions in which NO_3- may have some ergogenic proprieties are still unknown and further research is required. Notwithstanding, it is already known that dietary NO_3- supplementation effects depend on the subject, fitness status, food patterns, intensity and duration of the exercise, dose and time of intake. Moreover, athletes should be advised not to rise the mouth with the antibacterial mouthwash prior to the NO_3-supplementation.

References

1. Bailey SJ FJ. Dietary nitrate supplementation enhances muscle contractile efficiency during knee-extensor exercise in humans. J Appl Physiol (1985). 2010.
2. Lansley K, Winyard P, Bailey S, Vanhatalo A, Wilkerson D, Blackwell J, et al. Acute dietary nitrate supplementation improves cycling time trial performance. Medicine and Science in Sports and Exercise. 2011.
3. Alvares TS, Conte-Junior CA, Silva JT, Paschoalin VMF. Acute L-Arginine supplementation does not increase nitric oxide production in healthy subjects. Nutrition and Metabolism. 2012.
4. Ferreira L, Behnke B. A toast to health and performance! Beetroot juice lowers blood pressure and the O2 cost of exercise. Journal of Applied Physiology (1985). 2011.
5. Jones AM, Vanhatalo A, Bailey SJ. Influence of dietary nitrate supplementation on exercise tolerance and performance. Nestle Nutrition Institute workshop series. 2013;75:27-40.
6. Jones A. Dietary nitrate supplementation and exercise performance. Sports Medicine. 2014.
7. Moncada S, Higgs A. The L-arginine-nitric oxide pathway. The New England Journal of Medicine. 1993.
8. Totzeck M, Hendgen-Cotta U, Rammos C, Frommke L, Knackstedt C, Predel H, et al. Higher endogenous nitrite levels are associated with superior exercise capacity in highly trained athletes. Nitric Oxide. 2012.
9. Cermak N, Res P, Stinkens R, Lundberg J, Gibala M, LJ. VL. No improvement in endurance performance after a single dose of beetroot juice. International Journal of Sports Nutrition and Exercise Metabolism. 2012.
10. Boorsma R, Whitfield J, Spriet L. Beetroot juice supplementation does not improve performance of elite 1500-m runners. Medicine Science Sports Exercise. 2014.
11. Wilkerson D, Hayward G, Bailey S, Vanhatalo A, Blackwell J, Jones A. Influence of acute dietary nitrate supplementation on 50 mile time trial performance in well-trained cyclists. European Journal of Applied Physiology. 2012.
12. Hord NG, Tang Y, Bryan NS. Food sources of nitrates and nitrites: the physiologic context for potential health benefits. The American Journal of Clinical Nutrition. 2009.
13. Bailey S, Blackwell J, Williams E, Vanhatalo A, Wylie L, Winyard P, et al. Two

weeks of watermelon juice supplementation improves nitric oxide bioavailability but not endurance exercise performance in humans. Nitric Oxide. 2016.
14. Shanely R, Nieman D, Perkins-Veazie P, Henson D, Meaney M, Knab A, et al. Comparison of Watermelon and Carbohydrate Beverage on Exercise-Induced Alterations in Systemic Inflammation, Immune Dysfunction, and Plasma Antioxidant Capacity. Nutrients. 2016.
15. Meirelles C, Matsuura C. Acute supplementation of L-arginine neither affects strength performance nor nitric oxide production. The Journal of Sports Medicine and Physical Fitness. 2016.
16. Chowdhury A, Das A. Nitrate Accumulation and Vegetable Quality. International Journal of Science and Research (IJSR). 2013.
17. Jonvik K, Nyakayiru J, Van Dijk J, Wardenaar F, van Loon L, Verdijk L. Habitual Dietary Nitrate Intake in Highly Trained Athletes. International Journal of Sports Nutition and Exercise Metabolism. 2016.
18. Bescos R, Rodriguez F, Iglesias X, Ferrer M, Iborra E, Pons A. Acute administration of inorganic nitrate reduces VO(2peak) in endurance athletes. Medicine and Science in Sports and Exercise. 2011.
19. Cermak N, Gibala M, van Loon L. Nitrate supplementation's improvement of 10-km time-trial performance in trained cyclists. International Journal of Sports Nutrition and Exercise Metabolism. 2012.
20. Hoon M, Jones A, Johnson N, Blackwell J, Broad E, Lundy B, et al. The effect of variable doses of inorganic nitrate-rich beetroot juice on simulated 2,000-m rowing performance in trained athletes. International Journal of Sports Physiology and Performance. 2014.
21. Hoon M, Johnson N, Chapman P, Burke L. The Effect of Nitrate Supplementation on Exercise Performance in Healthy Individuals: A Systematic Review and Meta-Analysis. International Journal of Sport Nutrition and Exercise Metabolism. 2013.
22. Domínguez R, Cuenca E, Maté-Muñoz JL, García-Fernández P, Serra-Paya N, Estevan MCL, et al. Effects of Beetroot Juice Supplementation on Cardiorespiratory Endurance in Athletes. A Systematic Review. Nutrients. 2017.
23. Lundberg JO, Weitzberg E, Gladwin MT. The nitrate-nitrite-nitric oxide pathway in physiology and therapeutics. Nat Rev Drug Discov. 2008;7(2):156-67.
24. Bisnett T, Anzueto A, Andrade F, Rodney JG, Napier W, Levine S, et al. Effect of Nitric Oxide Synthase Inhibitor on Diaphragmatic Function after Resistive Loading. Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology. 1998.
25. Galler S, Hilber K, Gobesberger A. Effects of nitric oxide on force-generating proteins of skeletal muscle. Pflugers Arch: European Jounal of Physiology. 1997.
26. Kobzik L, Reid M, Bredt D, Stamler J. Nitric oxide in skeletal muscle. Nature. 1994.
27. Reid M. Role of nitric oxide in skeletal muscle: synthesis, distribution and functional importance. Acta Physiologica Scandinavica. 1998.
28. Reid M. Nitric oxide, reactive oxygen species, and skeletal muscle contraction. Medicine and Science in Sports and Exercise. 2001.
29. Fulford J, Winyard P, Vanhatalo A, Bailey S, Blackwell J, Jones A. Influence

of dietary nitrate supplementation on human skeletal muscle metabolism and force production during maximum voluntary contractions. Pflugers Arch: European Journal of Physiology. 2013.

30. Haider G, Folland J. Nitrate supplementation enhances the contractile properties of human skeletal muscle. Medicine and Science of Sports and Exercise. 2014.
31. Mosher S, Sparks S, Williams E, Bentley D, Mc Naughton L. Ingestion of a nitric oxide enhancing supplement improves resistance exercise performance. The Journal of Strength and Conditioning Research. 2016.
32. Flanagan S, Looney D, Miller M, DuPont W, Pryor L, Creighton B, et al. The Effects of Nitrate-Rich Supplementation on Neuromuscular Efficiency during Heavy Resistance Exercise. The Journal of the American College of Nutrition. 2016.
33. Coggan A, Leibowitz J, Kadkhodayan A, Thomas D, Ramamurthy S, Spearie C, et al. Effect of acute dietary nitrate intake on maximal knee extensor speed and power in healthy men and women. Nitric Oxide. 2015.
34. Hopkins W, Hawley J, Burke L. Design and analysis of research on sport performance enhancement. Medicine and Science of Sports and Exercise. 1999.
35. Hodges RR, Shatos MA, Tarko RS, Vrouvlianis J, Gu J, Dartt DA. Nitric oxide and cGMP mediate α1D-adregenic receptor-stimulated protein secretion and p42/p44 MAPK activation in rat lacrimal gland. Investigative Ophtalmology and Visual Science. 2006.
36. Maréchal G, Gailly P. Effects of nitric oxide on the contraction of skeletal muscle. Cellular and Molecular Life Sciences. 1999.
37. Clements W, Lee S, Bloomer R. Nitrate ingestion: a review of the health and physical performance effects. Nutrients. 2014.
38. Boutcher S. High-Intensity Intermittent Exercise and Fat Loss. Journal of obesity. 2011.
39. Wylie LJ, Bailey SJ, Kelly J, Blackwell JR, Vanhatalo A, Jones AM. Influence of beetroot juice supplementation on intermittent exercise performance. European Journal of Applied Physiology. 2016.
40. Aucouturiera J, Boissièrea J, Pawlak-Chaoucha M, Cuvelierb G, Gamelina F-X. Effect of dietary nitrate supplementation on tolerance to supramaximal intensity intermittent exercise. Nitric Oxide. 2015.
41. Wylie L, Mohr M, Krustrup P, Jackman S, Ermiotadis G, Kelly J, et al. Dietary nitrate supplementation improves team sport-specific intense intermittent exercise performance. European Journal of Applied Physiology. 2013.
42. Thompson C, Wylie L, Fulford J, Kelly J, Black M, ST M, et al. Dietary nitrate improves sprint performance and cognitive function during prolonged intermittent exercise. European Journal of Applied Physiology. 2015.
43. Peeling P, Cox G, Bullock N, Burke L. Beetroot Juice Improves On-Water 500 M Time-Trial Performance, and Laboratory-Based Paddling Economy in National and International-Level Kayak Athletes. International Journal of Sports Nutrition and Exercise Metabolism. 2015.
44. Nyakayiru J, Jonvik KL, Trommelen J, Pinckaers PJM, Senden JM, van Loon LJ, et al. Beetroot Juice Supplementation Improves High-Intensity Intermittent Type Exercise Performance in Trained Soccer Players. Nutrients.

2017.
45. Bellar D, Hatchett A, Judge L, Breaux M, Marcus L. The relationship of aerobic capacity, anaerobic peak power and experience to performance in CrossFit exercise. Biology of Sport. 2015.
46. Kramer SJ, Baur DA, Spicer MT, Vukovich MD, Ormsbee MJ. The effect of six days of dietary nitrate supplementation on performance in trained CrossFit athletes. Journal of the International Society of Sports Nutrition. 2015.
47. Porcelli S, Ramaglia M, Bellistri G, Pavei G, Pugliese L, Montorsi M, et al. Aerobic Fitness Affects the Exercise Performance Responses to Nitrate Supplementation. Medicine and Science of Sports and Exercise. 2015.
48. McConell G, Bradley S, Stephens T, Canny B, Kingwell B, Lee-Young R. Skeletal muscle nNOS mu protein content is increased by exercise training in humans. American Journal of Physiology: Regulatory, Integrative and Comparative Physiology. 2007.
49. Jonvik K, Nyakayiru J, van Loon L, Verdijk L. Can elite athletes benefit from dietary nitrate supplementation? Journal of Applied Physiology (1985). 2015.
50. Jones AM, Ferguson SK, Bailey SJ, Vanhatalo A, Poole DC. Fiber Type-Specific Effects of Dietary Nitrate. Exercise and Sport Sciences Reviews. 2016;44(2):53-60.
51. Webb AJ, Patel N, Loukogeorgakis S, Okorie M, Aboud Z, Misra S, et al. Acute blood pressure lowering, vasoprotective and anti-platelet properties of dietary nitrate via bioconversion to nitrite. Hypertension. 2008.
52. Larsen F, Weitzberg E, Lundberg J, Ekblom B. Effects of dietary nitrate on oxygen cost during exercise. Acta of Physiology (Oxf). 2007.
53. Zafeiridis A. The effects of dietary nitrate (beetroot juice) supplementation on exercise performance: A review American Journal of Sports Science. 2014;2(4):97 - 110.
54. Vanhatalo A, Bailey SJ, Blackwell JR, DiMenna FJ, Pavey TG, Wilkerson DP, et al. Acute and chronic effects of dietary nitrate supplementation on blood pressure and the physiological responses to moderate-intensity and incremental exercise. American journal of physiology Regulatory, integrative and comparative physiology. 2010;299(4):R1121-31.
55. Loh Y, Jakszyn P, Luben R, Mulligan A, Mitrou P, Khaw K. N-Nitroso compounds and cancer incidence: the European Prospective Investigation into Cancer and Nutrition (EPIC)-Norfolk Study. American Journal of Clinical Nutrition. 2011.
56. Butler A. Nitrites and nitrates in the human diet: Carcinogens or beneficial hypotensive agents? Journal of Ethnopharmacology. 2015.
57. Alexander J, Cockburn A, Cravedi J-P, Dogliotti E, Domenico AD, Fink-Gremmels J, et al. Opinion of the Scientific Panel on Contaminants in the Food chain on a request from the European Commission to perform a scientific risk assessment on nitrate in vegetables. The EFSA Journal. 2008.
58. Lundberg J, Larsen F, Weitzberg E. Supplementation with nitrate and nitrite salts in exercise: a word of caution. Journal of Applied Physiology (1985). 2011.
59. Spiegelhalder B, Eisenbrand G, Preussmann R. Influence of dietary nitrate on nitrite content of human saliva: Possible relevance to in vivo formation

of N-nitroso compounds. Food Cosmet Toxicol. 1976.
60. Carpentier A, Stragier S, Brejeon C, Poortmans J. Nitrate Supplementation, Exercise, and Kidney Function: Are There Detrimental Effects? Medicine and Science of Sports and Exercise. 2015.
61. Govoni M, Jansson E, Weitzberg E, Lundberg J. The increase in plasma nitrite after a dietary nitrate load is markedly attenuated by an antibacterial mouthwash. Nitric Oxide. 2008.
62. Bondonno C, Liu A, Croft K, Considine M, Puddey I, Woodman R, et al. Antibacterial mouthwash blunts oral nitrate reduction and increases blood pressure in treated hypertensive men and women. American Journal of Hypertension. 2015.
63. Bergeron MF, Mountjoy M, Armstrong N, Chia M, Côté J, Emery CA, et al. International Olympic Committee consensus statement on youth athletic development. British Journal of Sports Medicine. 2015.
64. Hernández A, Schiffer T, Ivarsson N, Cheng A, Bruton J, Lundberg J, et al. Dietary nitrate increases tetanic [Ca2+]i and contractile force in mouse fast-twitch muscle. The journal of physiology. 2012.
65. Poortmans JR, Gualano B, Carpentier A. Nitrate supplementation and human exercise performance: too much of a good thing? Current opinion in clinical nutrition and metabolic care. 2015.

Exercise periodization and Taleb's antifragility

José Afonso[1], Ivo Hilvoorde[2], Niek Pot[3], Alexandre Medeiros[4] and Len Almond[5]

In Memoriam

To our dearest Len Almond, who unfortunately has passed away after a long battle against cancer. This work would not have been possible without you. More than everything, thank you for your ever-stimulating presence and for constantly challenging us to bring about newer understandings of life and of sports sciences.

Introduction

Exercise periodization is a foundational concept of Training Theory and Methodology, being used extensively in performance and health settings (1, 2). A plethora of periodized models abound, but all share a set of core principles: (i) establishing dates for the main competitions and/or other relevant milestones; (ii) planning time slots for periods extending from a week to years; and (iii) elaborating load management with the aim of achieving peak performance at the intended moments, while at the same time avoiding states of overtraining (1-3). In sum, periodized programs focus on managing load variation rationally in an attempt to predict directions, magnitudes, and timings of intended adaptations.

However, performance is loosely defined and multidimensional in many sports, which complicates the act of quantifying load (4). Moreover, sports form is constantly changing, making its evaluation and prediction a complex matter (5). Many athletes perform very well in training sessions and evaluations, yet fail astonishingly in competition (6). And empirical research in highly-controlled performance settings such as strength training is not consensual in showing that periodized programs are superior to non-periodized programs (7). Overall, research has provided some support for varied training programs, but not necessarily for

---

1. Centre for Research, Formation, Innovation and Intervention in Sport. Faculty of Sport, University of Porto, Portugal
2. Faculteit Bewegingswetenschappen, Vrije Universiteit Amsterdam, Netherlands
3. Windesheim University of Applied Sciences, Netherlands
4. Institute of Physical Education and Sport, Federal University of Ceará, Brazil
5. School of Education, St Mary's University, United Kingdom

periodized training programs (8). A systematic review with meta-analysis comparing different periodized programs suggested that novelty or training variety, and not periodization per se, are important for stimulating further development of strength (9). Depending on the type of sport, this is an important indicator for performance.

A recent systematic review (10) focused on conceptual and methodological features of research on periodized training programs. Forty-two randomized or randomized controlled trials on periodized programs with human subjects were included, and the results were disappointing. First and foremost, the concepts of periodization and variation are being using interchangeably, as non-periodized programs are being wrongly equated with constant programs, i.e., programs that remain unchanged in time (e.g., same exercises, number of sets, number of repetitions, exercise sequence, and so on). Furthermore, constant programs might use progressive load (i.e., keep all variables constant, but increase load as one progresses), possibly improving performance. Secondly, no predictions concerning direction, magnitude, or timing of adaptations were tested. An additional number of methodological problems, such as poor control of confounding factors (e.g., nutrition, supplementation and medication), severely limits the claims of research. A common argument is that periodization might be more useful in individual sports, especially those of more closed nature (i.e., less contextual interference, such as swimming). However, this systematic review has shown that research has not provided support for the utilization of periodized programs, even in tightly-controlled scenarios as strength-training programs.

In this vein, Taleb's concept of antifragility (11) presents a possible alternate framework, a line of reasoning that deserves some testing. The author defined three main types of systems: (i) fragile systems, whose dynamics break down in the face of errors or unexpected events; (ii) robust systems, whose dynamics are largely immune to errors or unexpected events; and (iii) antifragile systems, evolving entities that actually use errors and perturbations has a developmental factor in improving their dynamics. Admittedly, dynamic systems theory has embraced the concept of perturbation and its importance for systemic behaviour (12, 13). Notwithstanding, systems react very differently to perturbations; it is only when errors and perturbations are used by the system to evolve (i.e., to change) that a system becomes *antifragile* (11). As such, antifragile systems are a specific subset of complex systems.

Therefore, our aim is to provide a critique of sports periodization making use of the concept of antifragility. Although this analysis is theoretically-driven, we hope to pinpoint novel ideas for research on the topic. This paper does not aim at establishing any doctrine, instead proposes that acritically accepted concepts are revisited and reanalysed using different lenses.

Antifragility and sports periodization

The majority of systems is moulded through dynamic exchanges with the environment in a permanent state of non-equilibrium; consequently, systemic behaviour evolves over time (14, 15), and the more complex a system, the less able we are of predicting its future behaviour (16). Highly stable (i.e., robust) systems are very difficult to perturb, so transitioning to a new behavioural state may be challenging (15). For example, literature on motor learning has alerted practitioners to the risks of highly automated and stereotyped movements, especially when the environment where they perform is variable (17). Antifragile systems benefit from and grow with errors, which become information-rich *opportunities for development* (11). In the language of motor learning, such systems benefit from a certain degree of contextual interference (17).

Antifragility presupposes a delicate interplay between systemic behaviours and environment. Periodized approaches, however, attempt to predetermine a sequential process beforehand (1-3). Even if linear relationships were predominant in response to training stimuli, the success of a given athlete in a certain competition using a prearranged periodized program would not be valid as an argument; in the end, we should ask whether alternative methods and means could have produced even better results (8). In fact, many athletes deliver great performances despite deviating from the training plans, while others don't achieve success despite following the training plans (18). And the numerous cases of unsuccess seldom make their way to widespread knowledge, yet they must be acknowledged to verify the real effectiveness of any periodized program (8).

Therefore, classical paradigms of stimulus-response are misapplied to dynamic systems (19), as dose-response relationships and development are non-linear in nature (11, 20). Non-linear relationships bring about *emergent* behaviour (21), meaning that the end-result cannot be predicted through a sum of the parts (22). Emergent behaviour implies self-organized *novelty* (23), and novelty is not (fully) predictable from previous information, although some aspects of it might be probabilistic stipulated (e.g., hysteresis) (12). Indeed, self-organization may be defined as the system organizing itself, but without there being a 'self', no agent intentionally doing the organizing (13). In addition, as the behaviour of complex systems is exquisitely sensitive to initial conditions, the smallest changes can result in ever-large changes over time (24), resulting in an amplification of fluctuations with time (22, 23). And, as the initial conditions of any given system can never be stipulated accurately enough (15, 24), valid and accurate baseline measurements of any feature of an athlete are utopic, so reliability of predictions should be questioned (6). This is extended to ongoing conditions.

There have been some so-called 'non-linear' periodized approaches to training (25). Contrarily to what their proponents state, these proposals are actually linear. Linear systems have some well-established mathematical properties: (i) the *sum of the functions* of each component is equal to the *function of the sum* of the components [$f(x) + f(y) = f(x + y)$]; and (ii) multiplying the function of x by a scalar must equal the function of multiplying x by a scalar [$\alpha f(x) = f(\alpha x)$]. When at least one of these conditions is not respected, a function is termed non-linear. Indeed, linear functions are but a specific case of non-linear functions (26). 'Non-linear' periodized approaches, however, expect that a given sum of processes will result in a prearranged outcome in a predetermined period.

While systems operating far from equilibrium give rise to singular events, subverting statistical generalizations (27), empirical research on periodization focus solely on average values (10). Non-linear functions render the average irrelevant; the important is the stability surrounding the average, i.e., the degree of dispersion or variation (11). But even when the average is an appropriate factor, it is still not relevant nor informative for each individual case (8, 28). Moreover, population distributions can never be empirically known, so the form and the specifics of each distribution are, in themselves, estimates (27). Taken together, this invites scientists and practitioners to question the accuracy of predictions based on momentary and necessarily limited evaluations.

Life is convoluted, yet our brains elaborate a coherent narrative, smoothing out inconsistencies in *a posteriori* rationalization (29). Training is no exception, with the predictive ideal of science clashing with the constraints and idiosyncrasies of daily practice. Postdictions create the illusion that we comprehend the world (11) and restructure the past to fit present beliefs, in an act of historical revisionism (30), and perhaps this illusion of prediction satiates the human need for living a coherent narrative. In this scope, and despite individual learning rates varying drastically (31), periodized training plans establish timelines for rhythms of learning (6). As paradigms are usually abandoned only a new paradigm is available (32), here we will attempt to elaborate an alternative paradigm to current periodized training programs.

Towards a new paradigm

The lack of scientific evidence in favour of periodized programs (10) may be temporary. Better conceptually and methodologically designed empirical research might justify its application. And even if the lack of current evidence is coupled with theoretical reasons for doubting the efficacy of periodization, this approach should not be discarded altogether. Nonetheless, this does suggest that distinct approaches should be experimented with. Indeed, alternatives to periodization should be tested, expanding our knowledge and options instead of focusing in a single paradigm. Thus, in what follows we will present two possible alternate frameworks, theoretical proposals that will require empirical testing.

A conservative line of action would follow a minimalist (i.e., periodize to the less extent possible and to the smaller devisable time lengths) and *negative* approach to periodization. The negative approach focuses on enumerating what should *not* be done (11), and draws an important parallel with the work of Sir Karl Popper (33) in socio-politics. In this minimalist and negative approach, periodized programs would be reduced to the basics, such as avoid having many consecutive weeks of training with extremely high volume and intensity, attempting to escape overtraining (34). Perhaps they could also establish strategic rest periods during the year, usually associated with pauses in the competition and/or culturally-specific holidays (e.g., the 4^{th} of July is the Independence Day in the U.S.A., but in many countries, it is merely a regular day), and perhaps delivering effects similar to those associated with tapering (35). This minimalist and negative approach would still be a form of periodization, albeit a ‘reduced’ form.

Even so, the specifics of load management and arrangement would remain open to ongoing evaluation of the process, fully recognizing that two persons will respond differently to the same stimulus, and that the same person will respond differently to the same stimulus in different moments (34). What is more, these inter- and intra-individual variations in response cannot be predicted in advance (22). Therefore, perhaps a more drastic confrontation with the paradigm of periodized training programs would be to abandon them altogether. The hard truth is that the world is too random and unpredictable to establish *precise* plans based on foreseeing the future (11, 24). The evolution of athletes is a non-linear process, filled with surprises and discontinuities (36). And random and unexpected incidents must come to be expected in sports performance (16).

Still, periodized programs provide a (false) sense of stability and control over the process (8). Perhaps such illusion is necessary; it may be a necessary condition to thrive in complex, uncertain environments, even if through self-fulfilling prophecy (37). However, it is when we believe to be experiencing a relatively stable period that insidious vulnerabilities tend to accumulate and generate problems (11). So perhaps we should focus on exposition to failure, making prediction irrelevant. Practicing alternative gameplays, for example, might provide a team with more resources to deliver a solid performance in varying contexts and conditions. Even non-competitive settings may appeal to such logic. Contemporary dance also promotes dealing with the unexpected instead of anticipating actions, exploring momentary constraints and affordances and incorporating them into the dancers' movements (38). In fact, elite performers vary widely in their executions, and the same person performs differently as time passes (39).

Therefore, the determination of the contents that will be taught or coached should not be defined *a priori*, but elaborated based on continuous observation (40). Contrarily to periodized approaches, non-periodized (but varied) approaches *procrastinate*. Therefore, when decisions are effected, they are temporally closer to the action. Thus, by not having such a rigid, pre-stipulated framework, we are better prepared to grasp and explore emerging opportunities (8, 11). Postponing our planning decisions is more compatible with promoting the emergence of innovative processes and solutions in sports performance, as functional solutions can only emerge following exploration and discovery (41). Although we cannot predict which events will impact our coaching processes, it is possible to establish *options*, which largely reduces the need to rely on anticipatory evaluations (11). The focus would be on preparing players for *un*predictability (42), as learning to improve our capacity to correct course might be more relevant and decisive than predicting the course. Even in sports such as weightlifting or cycling, significant modifications of biomechanics in function of how an athlete will respond to training are warranted, and some such alterations cannot be determined in advance.

In this vein, athletes should develop a degree of redundancy, a fundamental risk-managing property in natural systems (11). Adaption to exercise actualizes the principle of redundancy, usually known as *overcom-*

pensation (34): after bouts of acute exercise, the body surpasses its initial state, thereby being better prepared for future aggressions. Conversely, detraining produces the opposite effect. Thus, the body manages the degree of redundancy required depending on the regularity and intensity of the aggression it has to cope with. By developing redundancy (e.g., learning additional technical resources; exploring alternative tactical structures) the system becomes better prepared to face a more varied array of possible events. Degeneracy (i.e., the ability of structurally different elements in performing the same function) should be incorporated in our mindset, acknowledging the existence of several performance solutions (41, 43), recognizing that multiple degrees of freedom enable performers to complete tasks in various ways (15). This renders an optimal, idealized solution a utopic golem (8, 44).

Final considerations

Frequently, depictions of coaching and training highlight the planned, coordinated, rationalized part of the activity (36, 45). Periodization is a very human creation that attempts to divide a sports season into supposedly rational phases and cycles (18). The belief that it is possible to delineate time periods and manage responses to pre-stipulated load curves (2) provides a sense of power and control over the process, and the sheer repetition of an idea has a remarkable ability to get us to accept it (46). But analyses concerning peak performance in selected sports (including Track & Field) have shown that periodized approaches present very low rates of effectiveness (3). The works of Carpinelli and colleagues (7), Kiely (8) and, more recently, Afonso and colleagues (10) raised further doubts concerning the trustworthiness and scope of research on periodized training programs.

Compartmentalisation of human performance into basic and specific capacities and regulation of overload and supercompensation in specific timings of the training cycle are not grounded on physiological evidence (3, 8). Furthermore, our inability to foresee the future, to deal with probabilities, to calculate chain events, secondary effects and unintended consequences (26, 30), can result in an iatrogenic effect, provoking more harm than good (11). A very interesting discussion of the problems with predicting performance when applied to talent detection and selection is presented by Ackerman (31). Paradoxically, by attempting to pre-establish the process to a large extent and make predictions based on theoretical models, periodization may increase a system's fragility, increasing the risk of exposition to unexpected events.

A broad, loosely-defined planning might be best suited to a dynamic, evolving process, in comparison to a periodized approach. This would allow *effectively* respecting the principle of individualization. Inter- and intra-individual variation in response to external loads find strong support in the literature (4, 34, 47). What suits a given athlete might be prejudicial to another, and the same subject will respond distinctively in different moments (5, 8, 22, 31). There are non-responders to different types of resistance training (48), altitude training (49), cardiac resynchronization therapy (50), pulmonary rehabilitation (51), among others.

Pre-established programs are always delusive, especially when literature on expertise and career planning have shown that many elite athletes have failed talent detection programmes and performed poorly on standardized physical batteries (17, 52). Commenting on Long-Term Athlete Development (LTAD), the National Strength and Conditioning Association stated that LTAD pathways should accommodate for the highly individualized and non-linear nature of development, recognizing the existence of significant interindividual variance regarding magnitude of change, timing (onset of change), and tempo (rate of change) of biological processes, therefore impacting profoundly on each athlete's trainability (53). Overall, generic methodologies are likely to fail (8).

Mainstream thinking, however, is still hostage to the ideal of Quételet's *homme moyen* and, in sports, to the ideal of the optimal movement pattern (42, 47). Worldviews are frameworks that present a vision of the nature of the world (32), and the practices motivated by such worldviews tend to crystalize and become discursive 'truths' (45). Periodization relies on the worldview of a predictable world, where complexity and unpredictability can somehow be encapsulated into pre-planned frameworks (8). This worldview is common to economic models, despite evidence repeatedly showing these models fail amazingly (26, 54). Peer pressure and cultural inertia weigh considerably, and novel ideas, especially if breaking away with established paradigms, threaten our deeply engrained beliefs (41). Notwithstanding, it is only when individuals break with current thinking in a given field that new ideas and concepts can flourish and bring about a new status quo (55).

In this context, we believe that Taleb's concept of an antifragile system and its implications for developmental processes should be incorporated into training theory and methodology. Perhaps it is time to acknowledge the full implications of the ambiguous and unpredictable nature of coaching (56), namely that performance and learning environments can rarely be planned and prescribed in advance (21). We should shift the focus from prediction to preparation (26), using open-ended and highly-flexible approaches to planning (6, 57), i.e., use simple, suggestive and flexible plans and modify them according to the athlete's actual progression (58). Planning should be a *generic* perspective, a letter of intentions *without* venturing into details, an outline of basic starting points, checkpoints and endpoints with only a sparse skeleton (8). The coach then orchestrates the process as it unfolds (57). The training session or the class unit are the fundamental entities of the process (58).

References

1. Issurin VB. Block periodization versus traditional training theory: A review. . Journal of Sports Medicine and Physical Fitness. 2008;48:65-75.
2. Naclerio F, Moody J, Chapman M. Applied periodization: a methodological approach. Journal of Human Sport and Exercise. 2013;8:350-66.
3. Loturco I, Nakamura F. Training periodisation. An obsolete methodology? Aspetar Sports Medicine Journal. 2016;5:110-5.
4. Mujika I. Challenges of team-sport research. International Journal of Sports Physiology and Performance. 2007;2:221-2.
5. Lames M. Computer science for top-level team sports. International Journal of Computer Science in Sport. 2003;2:57-72.
6. Denison J, Mills J. Planning for distance running: coaching with Foucault. Sports Coaching Review. 2014;3:1-16.
7. Carpinelli RN, Otto RM, Winett RA. A critical analysis of the ACSM Position Stand on resistance training: insufficient evidence to support recommended training protocols. Journal of Exercise Physiology Online. 2004;7:1-60.
8. Kiely J. Periodization paradigms in the 21st century: evidence-led or tradition-driven? International Journal of Sports Physiology and Performance. 2012;7:242-50.
9. Harries S, Lubans D, Callister R. Systematic review and meta-analysis of linear and undulating periodized resistance training programs on muscular strength. Journal of Strength and Conditioning Research. 2015;29:1113-25.
10. Afonso J, Nikolaidis PT, Sousa P, Mesquita I. Is empirical research on periodization trustworthy? A comprehensive review of conceptual and methodological issues. Journal of Sports Science and Medicine. 2017;16:27-34.
11. Taleb NN. Antifragile: Things that gain from disorder: Nassim Nicholas Taleb; 2012.
12. Haken H. Synergetics: Nonequilibrium phase transitions in Physics, Chemistry and Biology. Berlin: Springer; 1977/83.
13. Kelso JAS. Dynamic patterns. The self-organization of brain and behavior: Mit Press; 1995.
14. McGarry T, Anderson D, Wallace S, Hughes MD, Franks IM. Sport competition as a dynamical self-organizing system. Journal of Sports Sciences. 2002;20:771-81.
15. Van Emmerik REA, Ducharme SW, Amado AC, Hamill J. Comparing dynamical systems concepts and techniques for biomechanical analysis. Journal

of Sport and Health Science. 2016;5:3-13.
16. Aicinena S. The impact of chaos, complexity, and luck on coaching success. International Journal of Society, Science & Education. 2013;3:551-65.
17. Schmidt R, Wrisberg C. Motor learning and performance. A situation-based learning approach (4th Ed.). Champaign, Illinois: Human Kinetics; 2008.
18. Denison J, Scott-Thomas D. Michel Foucault: Power and discourse: the ‘loaded’ language of coaching. In: Jones R, Potrac P, Cushion C, Ronglan LT, editors. The sociology of sports coaching. New York: Routledge; 2011. p. 27-39.
19. McGarry T, Franks IM. System approach to games and competitive playing: reply to Lebed (2006). European Journal of Sport Science. 2007;7:47-53.
20. Overton W. Taking conceptual analyses seriously. Research in Human Development. 2015;12:163-71.
21. Davids K. Learning design for nonlinear dynamical movement systems. The Open Sports Sciences Journal. 2012;5:9-16.
22. Rowland T. The athlete’s clock. How biology and time affect sport performance. Champaign, Illinois: Human Kinetics; 2011.
23. Latash M. Neurophysiological basis of movement (2nd Ed.). Champaign, Illinois: Human Kinetics; 2008.
24. Saltzstein P. Chaos & An Unpredictable Tomorrow. Philosophy Now 2016;114.
25. Hasegawa H, Dziados J, Newton R, Fry A, Kraemer W, Häkkinen K. Periodized training programs for athletes. In: Kraemer W, Häkkinen K, editors. Strength Training for Sport: Wiley-Blackwell; 2002. p. 69-134.
26. Taleb NN. The Black Swan: The impact of the highly improbable: Random House; 2006.
27. Hendry D, Mizon G. Unpredictability in economic analysis, econometric modeling and forecasting. Journal of Econometrics. 2014;182:186-95.
28. Gigerenzer G, Brighton H. Homo Heuristicus: why biased minds make better inferences. Topics in Cognitive Science. 2009;1:107-43.
29. Damásio A. Descartes’ Error: Emotion, reason, and the human brain: Putnam Publishing; 1994.
30. Schön D. Educating the reflective practitioner. Toward a new design for teaching and learning in the professions. San Francisco: Jossey-Bass Publishers; 1987.
31. Ackerman P. Nonsense, common sense, and science of expert performance: Talent and individual differences. Intelligence. 2014;45:6-17.
32. Overton W. The process-relational paradigm and relational-developmental-systems metamodel as context. Research in Human Development. 2014;11:323-31.
33. Popper K. The open society and its enemies, Vol. 1: The spell of Plato (5th Rev Edition: Princeton University Press; 1971.
34. Kenney WL, Wilmore JH, Costill DL. Physiology of Sport and Exercise (5th Ed.). Champaign, Illinois: Human Kinetics; 2012.
35. Pyne D, Mujika I, Reilly T. Peaking for optimal performance. Research limitations and future directions. Journal of Sports Sciences. 2009;27:195-202.
36. Bowes I, Jones R. Working at the edge of chaos: understanding coaching as a complex, interpersonal system. The Sport Psychologist. 2006;20:235-45.

37. Merton RK. The self-fulfilling prophecy. Antioch Review. 1948;8:193-210.
38. Louppe L. Poetic of contemporary dance. [Portuguese original title: Poética da dança contemporânea]. Lisboa: Orfeu Negro; 2012.
39. Bailey R, Pickard A. Body learning: examining the processes of skill learning in dance. Sport, Education & Society. 2010;15:367-82.
40. Gréhaigne J-F, Wallian N, Godbout P. Tactical-decision learning model and students' practices. Physical Education and Sport Pedagogy. 2005;10:255-69.
41. Renshaw I, Araújo D, Button C, Chow JY, Davids K, Moy B. Why the Constraints-Led Approach is not Teaching Games for Understanding: A clarification. Physical Education and Sport Pedagogy. 2016;21:459-80.
42. Passos P, Araújo D, Davids K, Shuttleworth R. Manipulating constraints to train decision making in Rugby Union. International Journal of Sports Science & Coaching. 2008;3:125-40.
43. Glazier P, Davids K. Constraints on the complete optimization of human motion. Sports Medicine. 2009;39:15-28.
44. Lederman E. The fall of the postural-structural-biomechanical model in manual and physical therapies: Exemplified by lower back pain. Journal of Bodywork and Movement Therapies. 2011;15:131-8.
45. Denison J. Planning, practice and performance: the discursive formation of coaches' knowledge. Sport, Education & Society. 2010;15:461-78.
46. Varki A, Brower D. Denial. Self-deception, false beliefs, and the origins of the human mind. New York: Twelve; 2013.
47. Davids K, Button C, Bennett S. Dynamics of skill acquisition. A constraints-led approach. Champaign, Illinois: Human Kinetics; 2008.
48. Jones N, Kiely J, Suraci B, Collins DJ, de Lorenzo D, Pickering C, et al. A genetic-based algorithm for personalized resistance training. Biology of Sport. 2016;33:117-26.
49. Hamlin M, Manimmanakorn A, Sandercock G, Ross J, Creasy R, Hellemans J. Heart rate variability in responders and non-responders to live-moderate, train-low altitude training. World Academy of Science, Engineering and Technology. 2011;77:936-40.
50. Auricchio A, Prinzen F. Non-responders to cardiac resynchronization therapy. The magnitude of the problem and the issues. Circulation Journal. 2011;75:521-7.
51. Stoilkova-Hartmann A, Janssen D, Franssen F, Wouters EF. Differences in change in coping styles between good responders, moderate responders and non-responders to pulmonary rehabilitation. Respiratory Medicine. 2015;109:1540-5.
52. Pinder R, Renshaw I, Davids K. The role of a representative design in talent development: a comment on 'Talent identification and promotion programmes of Olympic athletes'. Journal of Sports Sciences. 2013;31:803-6.
53. Lloyd RS, Cronin JB, Faigenbaum AD, Haff GG, Howard R, Kraemer WJ, et al. National Strength and Conditioning Association position statement on long-term athletic development. Journal of Strength and Conditioning Research. 2016;30:1491-509.
54. Krugman P. The return of depression economics and the crisis of 2008: W. W. Norton & Company; 2009.

55. Olszewski-Kubilius P, Subotnik R, Worrell F. Antecedent and concurrent psychosocial skills that support high levels of achievement within talent domains. High Ability Studies. 2015;26:195-210.
56. Barker E, Bailey J. There's more to coaching than the context: a Bourdieusian account of an embodied athlete. Sports Coaching Review. 2015;4:41-7.
57. Jones R, Wallace M. Another bad day at the training ground: coping with ambiguity in the coaching context. Sport, Education & Society. 2005;10:119-34.
58. Bompa T. Periodization. Theory and methodology of training (4th Ed.). Champaign, Illinois: Human Kinetics; 1999.

Effects of different rest intervals between potentiation exercises on sprint performance in trained soccer players

Vasiliki Manou[1], Vasilis Minos[1], Athanasios A. Dalamitros[1]

Introduction

A variety of different training methods and techniques have been used by strength and conditioning practitioners and sports scientists to enhance sports performance. Towards this direction, the post-activation potentiation phenomenon (PAP) (Robbins & Docherty, 2005) has drawn increasing attention as a relatively new concept. To exploit this phenomenon during sports training, the complex method is used (Docherty et al., 2004). This training method refers to the condition where the execution of a previous high-intensity activity may induce short-term performance during explosive athletic movements such as jumps, sprints and throws.

The proposed mechanisms responsible for PAP have previously been suggested (Tillin & Bishop, 2009), while the response magnitude of PAP is depended on multiple variables such as gender and chronological age (Arabatzi et al., 2014), genetics (Hamada et al., 2000), as well as training characteristics and methodological issues (exercise volume and intensity, recovery interval, movement and muscle contraction type) (Esformes & Bambouras, 2011; Wilson et al., 2013). Training status has been also denoted as an important parameter affecting PAP responses, while stronger or power trained individuals seem to be benefitting the most (Seitz et al., 2014). In addition, PAP effect is larger for sprint performance, compared to jumping and throwing activities (Seitz & Haff, 2015). Based on the above observations, PAP is presented as an individualized and multifaceted phenomenon.

The efficacy of PAP has been examined in numerous sports such as rowing (Doma et al., 2016), swimming (Sarramian et al., 2015), in track and field athletes (Ountzoudi et al., 2014), basketball (Tsimachidis et al., 2013) and rugby (Bevan et al., 2009). Soccer is an activity where PAP has a practical application, as explosive activities (e.g. sprints) are of great importance. High-level soccer players spend approximately 11% of their game in sprinting activities, while the short duration sprints (< 5 s) ac-

1. Faculty of Physical Education & Sport Sciences, School of Physical Education & Sport Sciences, Aristotle University of Thessaloniki, Greece

count to 90% of the overall sprints (Andrzejewski et al., 2013). Thus, it is not surprising that acute (Low et al., 2015; McBride et al., 2005; Rahman, 2007) and longitudinal studies (Brito et al., 2014; Maio Alves et al., 2010) have been focused on the PAP, or complex training method effect on sprint performance in distances varying from 5 to 40 m in soccer players of different training levels demonstrating improved running times. In all these cases, the preceding activity was the heavy load back squat exercise with intensities equal or above 85% of the athletes' one repetition maximum (1RM).

As earlier mentioned, recovery interval times consist a major determinant for PAP responses. A previous study that examined six different recovery times (15s, 4, 6, 8, 12 and 20 minutes) during a potentiation protocol consisting of a 3RM squat exercise, failed to provide a specific guideline regarding the optimal recovery period for vertical jumping performance (peak power and jump height) in professional soccer players (Mola et al., 2014). However, most of the responders demonstrated an optimal PAP "window" at the 4 min recovery time. The same interval period (4 minutes) was also prescribed in the study of Rahimi (2014), presenting improved 40 m sprint times in elite soccer players after a loaded (85% of 1RM) squat exercise. From a practical point of view when working in a team setting, long recovery times between sets (e.g., 6 to 20 minutes) are difficult to be applied, since during a conditioning program the total exercise time generally does not exceed a 20 min time frame.

Interestingly, when analysing the methodological approaches regarding the potentiation protocols applied in studies using soccer players, a differentiation in the number of exercises preceding the "goal" activity is acknowledged. More analytically, a combination of strength (loaded squat exercise) and plyometric exercises (unloaded vertical jumps) was used in the studies examining the effects of a training program, while a single activity was implemented (loaded squat or loaded vertical jumping exercise) during the acute-type studies.

Nevertheless, the training adaptations previously reported could be solely attributed to the complex training intervention program applied in these studies. Hence, the necessity for examining the acute effects of a potentiation protocol including both strength and plyometric exercises has raised, since the possible fatigue manifestation is a critical parameter for the subsequent activity (DeRenne, 2010). Moreover, to the author's knowledge, no study to date has investigated the effect of different rest interval approaches during a potentiation activity and a plyometric type exercise on the subsequent running sprint performance of various distances. Therefore, the aim of this study was to analyse the acute effect of a potentiation protocol including a heavy load back squat exercise followed by an unloaded countermovement exercise, executed with three different rest interval strategies on the subsequent acceleration time (5 m), and sprint performance (20 - 30 m) in semi-professional male soccer players.

Methods

Participants

Forty-five adult male soccer players (age 22.2 ± 4.4 yrs, height 175.7 ± 6.9 cm, body mass 69.9 ± 6.6 kg, training experience 9.4 ± 2.6 yrs, 1RM back squat 97.2 ± 9.6 kg) from 2 different clubs were recruited during their competition phase and volunteered to participate in this study. They were all engaged in a training program 5 times per week, including 1 session of resistance training and had a minimum 2 years of experience in performing back squats. In addition, they were familiar with vertical jumping exercises. All athletes had no current injuries, while the exclusion criteria included lower body myoskeletal pain within the preceding two-week time frame. In addition, they were requested to abstain from alcohol consumption for 24 hours, and to avoid any strenuous exercise the day before testing. All participants provided informed consent with all procedures approved by the Institutional Human Research Ethics Committee and in accordance with the Declaration of Helsinki.

Procedures and measures

Participants completed a 3-day testing procedure. Before the initiation of this period, a baseline sprint test including the assessment of the 5 m acceleration time (S5), the maximal 20 m (S20) and 30 m sprint times (S30) was performed (BASE). Two trials were allowed for each athlete, while the single highest score for the S30 was used for further analysis. During the same occasion, a familiarization session was completed. The 1RM determination was conducted according to the NSCA guidelines (Baechle & Earle, 2008) on a different occasion. As the depth of the squat exercise may influence the potentiation and the subsequent performance (Esformes & Babouras, 2013), a member of the research personnel was responsible for controlling a 90° knee angle and ensuring the proper technique. During the countermovement activity (CMJ) participants executed 8 maximal vertical jumps at a self-selected depth, starting from an upright position, with their hands on the waist. Sprint performance was evaluated in a straight 30 m line, in an artificial turf ground. Four pairs of photoelectric cells (STC3/ACCO58) with an electronic timer (Microgate Race Time 2, Italy) were placed 70 cm from the ground level on the starting line, at 5, 20 and 30 m. Each athlete began with the front foot placed 30 cm behind the starting line with a standing start (Ramírez-Campillo et al., 2016). The three testing sessions were performed at the same time of the day (early afternoon) with one week apart and were randomized using a counterbalanced design. Finally, environmental conditions were almost similar during the testing sessions.

After an identical warm-up (10 min including low intensity running, dynamic stretches, slow bodyweight back-squats, fast CMJ's and sprints), and following a 2 min rest, the athletes executed one of the three different potentiation protocols. During the first protocol (EXP_1), athletes executed the 6RM back squat exercise (85% of their 1RM) and the CMJ exercise, while a 4 min rest was allowed between the two activities. In this case, the subsequent 30 m sprint test was executed exactly after the plyometric exercise. The second potentiation strategy (EXP_2) included the same exercise order, with no rest interval between the heavy load activity and the plyometric exercise. After an equal rest interval (4 min), the 30 m sprint test was performed. Finally, during the third protocol (EXP_3), two passive rest intervals of equal duration (2 minutes) were placed after the back-squat activity and the CMJ exercise, before the sprint assessment. Strong verbal encouragement was given during all tests, while participants were instructed to wear the same shoes during the 3 testing occasions. The experimental design is demonstrated in Figure 1.

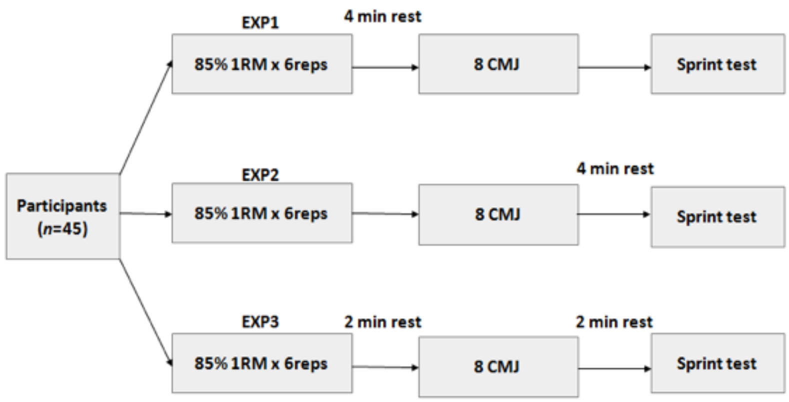


Figure. 1 Experimental design of the study.

Statistical Analysis

A one-way repeated measures analysis of variance (ANOVA) was used to examine differences between the baseline test and the potentiation protocols. Paired samples t-tests with a Bonferroni's correction were used to analyse between conditions differences. Cohen's d effect sizes (d = difference between means ¸ pooled SD) were calculated for the difference between means. The small, medium, and large effects were reflected in values greater than 0.20, 0.50, 0.80, respectively (Cohen, 1988). All statistical analyses were performed using SPSS 22.0 (IBM, New York, NY, USA). Statistical significance was set at $p \leq 0.05$. Data are expressed as means ± *SD* values.

Results

ANOVA with repeated measures revealed a significant condition effect at S5 ($F_{3,132} = 8.39$, $p \leq 0.001$), S20 ($F3,132 = 22.31$, $p \leq 0.001$) and S30 times ($F_{3,132} = 31.27$, $p \leq 0.001$). Values were faster during EXP_3 protocol, whereas all sprint tests were slower during EXP_1 protocol (Table 1).

	BASE	EXP_1	EXP_2	EXP_3	BASE vs. EXP_1	BASE vs. EXP_2	BASE vs. EXP_3
S5	1.008 ± 0.072	1.034 ± 0.078	1.007 ± 0.641	0.991 ± 0.064	ES = 0.35	ES = 0.00	ES = -0.24
S20	3.001 ± 0.126	3.033 ± 0.137	2.977 ± 0.124	2.945 ± 0.115	ES = 0.24	ES = -0.19	ES = -0.41
S30	4.192 ± 0.160	4.228 ± 0.175	4.168 ± 0.149	4.119 ± 0.156	ES = 0.21	ES = -0.16	ES = -0.48

Table 1. Mean ± SD values of the acceleration (5 m) and maximal 20 and 30 m sprint times (s) during the baseline test and after the three different potentiation protocols. Effect size (*ES*) is also presented (*n*=45).

BASE: Best 30 m sprint test during the familiarization session; EXP_1: 4 min rest between Squat and CMJ; EXP_2: 4 min rest after CMJ; EXP_3: 2 min rest after Squat and CMJ; S5 = Acceleration time 5 m; S20 = Sprint time at 20 m; S30 = Sprint time at 30 m.

Paired samples t-tests revealed a significant statistical difference between almost all tested conditions ($p = 0.000$ to 0.036), while a small to medium effect size was observed between testing conditions (≤ 0.50). As an, exception BASE and EXP_2 values for S5 test were almost identical (p =

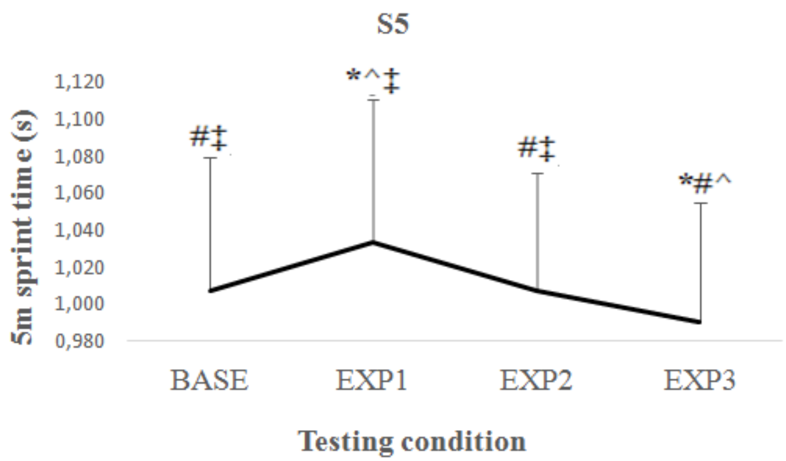


Figure 2. Results for acceleration time for all testing conditions; *Significantly different from BASE at *p* value; # Significantly different from EXP1 at p value; ^ Significantly different from EXP2 at p value; ‡ Significantly different from EXP3 at p value; BASE: Best 30 m sprint test during the familiarization session; EXP1: 4 min rest between Squat and CMJ; EXP2: 4 min rest after CMJ; EXP3: 2 min rest after Squat and CMJ; S5 = Acceleration time 5 m; S20 = Sprint time at 20 m; S30 = Sprint time at 30 m.

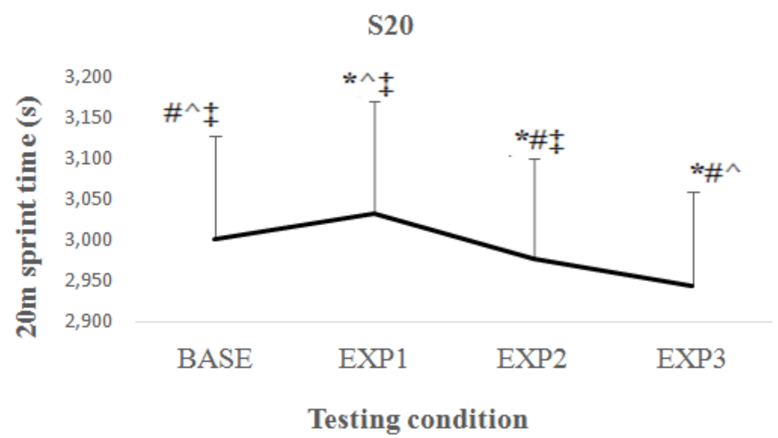


Figure 3. Results for maximal 20 sprint time for all testing conditions; *Significantly different from BASE at *p* value; # Significantly different from EXP1 at p value; ^ Significantly different from EXP2 at p value; ‡ Significantly different from EXP3 at p value; BASE: Best 30 m sprint test during the familiarization session; EXP1: 4 min rest between Squat and CMJ; EXP2: 4 min rest after CMJ; EXP3: 2 min rest after Squat and CMJ. S5 = Acceleration time 5 m; S20 = Sprint time at 20 m; S30 = Sprint time at 30 m, as these info are missing from this note (Check Figures 1, 2 and 4).

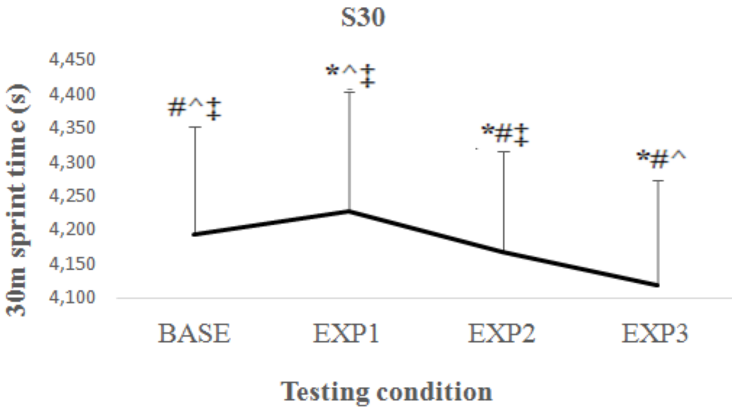


Figure 4. Results for maximal 30 sprint time for all testing conditions; *Significantly different from BASE at p value; # Significantly different from EXP1 at p value; ^ Significantly different from EXP2 at *p* value; ‡ Significantly different from EXP3 at p value; BASE: Best 30 m sprint test during the familiarization session; EXP1: 4 min rest between Squat and CMJ; EXP2: 4 min rest after CMJ; EXP3: 2 min rest after Squat and CMJ. S5 = Acceleration time 5 m; S20 = Sprint time at 20 m; S30 = Sprint time at 30 m.

Discussion

Post-activation potentiation phenomenon has gained considerable research interest, whereas its practical application is commonly used to optimize performance in various sports activities. This study aimed to analyze the effect of three different rest interval approaches during a potentiation protocol, including both strength and plyometric activities, on the subsequent acceleration and maximal sprint time in trained soccer players. According to the results, EXP_3 was presented as the most effective strategy as an acute significant reduction in S5, S20 and S30 performance times was observed, compared to BASE test, as well as the rest of the potentiation protocols applied. S20 and S30 m times were also significantly improved after executing EXP_2 strategy, compared to BASE test. Interestingly, EXP_1 potentiation protocol concluded to significantly slower times during all distances evaluated compared to the rest of the potentiation protocols and BASE test. Finally, S5 times were almost identical between BASE and EXP_2 approaches.

Despite not being a biomechanically similar movement pattern, loaded back squat strength values are closely related to sprint performance during 10 and 30 m distances in soccer players (Wisløff et al., 2004), since the same muscle groups contributing to running sprint are activated (Newman et al., 2004). This exercise is regularly used as a potentiation activity to acutely enhance sprint performance in soccer demonstrating a positive effect in sprint distances up to 40 m (Low et al., 2015; McBride et al., 2005; Rahimi, 2007). 1RM mean squat value in our study (97.2 kg) was somewhat similar to the squat load denoted by Mola et al. (2014) (~100 kg), but also significantly lower compared to a previous report (171.7 kg) (Wisløff et al., 2004) in a sample of professional soccer players. According to Jo and colleagues (2010), the respective values for recreational soccer players were 83.6 kg. Considering these values, we could describe our participants' strength level as "moderate".

The rest interval implemented in the current study (4 min) could not be characterized as "optimal", according to previous reports examining PAP manifestation on the subsequent sprint performance (Crewther et al., 2011; Mola et al., 2014). In fact, a recent meta-analysis proposed an adequate rest interval period of 7 to 10 minutes (Wilson et al., 2013). Even so, the 4 min rest interval has been applied in numerous studies (for a review, see Healy et al., 2017). However, we chose to apply this methodology, as one of our main objectives was to closely simulate an actual training program occur during a conditioning session in soccer.

During game analysis, 10 to 15 m sprint distances are usually performed every 90 seconds by professional soccer players (Withers et al., 1982). Moreover, up to 36 jumps are executed by a soccer player during a game situation (Mohr et al., 2003), usually preceding a sprint activity. This representation of training and game conditions could partially explain the fact that the shorter rest interval approach (2 min) concluded to the most noticeable results among the different strategies applied in this study. Another suggestion for this outcome could be that the CMJ probably impacted as an accumulated potentiation activity, even though it was executed in an unloaded manner. Indeed, a greater PAP response realized during a shorter time interval (0.3 - 4 min) has been observed after the completion of an unloaded plyometric exercise, compared to activities characterized by a high-intensity stimulus since less fatigue is produced (Seitz & Haff, 2015). Regarding the slower sprint times in S5, S20 and S30 observed during the EXP1 protocol compared to the baseline test, we could hypothesize that the power exercise performed with no rest interval prior to the sprint test may cause a reduction in the participants' ability for force production, resulting in decreased sprint performance. Nevertheless, in the absence of a neuromuscular activation test (such as EMG), this hypothesis can only be assumed.

Complex training, including the combination of heavy resistance and plyometric exercises executed in the same session, is presented as a time-efficient method for the concurrent improvement of both muscular strength and power abilities (Ebben, 2002), especially during the in-season period where the time for strength and conditioning programs is limited. The development of these abilities is considered highly crucial during game situations, as they are associated with more effective jumps, kicks and tackles (Stolen et al., 2005) and improved repeated sprint performance (Bogdanis et al., 2011). Therefore, the optimization of complex training programs is of interest in soccer for improving athletes' fitness level as well as transferring these gains to specific technical skills (Brito et a.l, 2014). Despite the existence of only trivial to small effect size, the results presented in this study are likely to have a practical application and are expected to facilitate soccer coaches and strength and conditioning practitioners towards the improvement of athletes' fitness level, supplementary to the acceleration and maximal running sprint enhancement.

The current study has several strengths (i.e., large number of trained soccer players, testing during actual training conditions, counter-balanced design). However, some limitations need to be addressed. First, given that maximum potentiation effects vary among athletes with different strength status, an inclusion criterion related to the 1RM back squat exercise should have been inserted. However, the relatively small SD value for the 1RM back squat observed (± 9.6kg) indicates a small variability within the participants. Second, exercise intensity during the CMJ execution was not controlled. Even though this exercise was not the potentiation activity in our study, different levels of effort may influence the outcome. Nevertheless, strong verbal encouragement was given throughout all testing sessions. Finally, the evaluation of the players' rate of perceived exertion might have assisted in more detailed results. Future studies should aim to address these issues.

Conclusions

The results of this study clearly present the effectiveness of a PAP strategy including a heavy loaded back squat exercise with a 2-min passive rest interval and an unloaded vertical jumping exercise following the same rest period, for enhancing the subsequent acceleration (5 m) and maximal sprint times (20 & 30 m) in semi-professional male soccer players. This potentiation strategy was also found superior in improving the above-mentioned variables, compared to the rest of the protocols applied and structured with different rest intervals. Finally, the data presented here indicate that by eliminating the rest interval between a plyometric exercise and a sprint test may conclude to the opposite effects.

References

Andrzejewski, M., Chmura, J., Pluta, B., Strzelczyk, R., Kasprzak, A.J. (2013). Analysis of sprinting activities of professional soccer players. Journal of Strength & Conditioning Research, 27(8): 2134-2140.

Arabatzi, F., Patikas, D., Zafeiridis, A., Giavroudis, K., Kannas, T., Gourgoulis, V., Kotzamanidis, C.M. (2014). The post-activation potentiation effect on squat jump performance: age and sex effect. Pediatric Exercise Science, 26(2): 187-94.

Baechle, T.R., Earle, R.W. (2008). Essentials of strength and conditioning (2nd ed.). Champaign, IL: Human Kinetics.

Bevan, H.R., Cunningham, D.J., Tooley, E.P., Owen, N.J., Cook, CJ., Kilduff, L.P. (2010). Influence of postactivation potentiation on sprinting performance in professional rugby players. Journal of Strength & Conditioning Research, 24(3):701-5.

Bogdanis, G.C., Papaspyrou, A., Souglis, A.G., Theos, A., Sotiropoulos, A., Maridaki, M. (2011). Effects of two different half-squat training programs on fatigue during repeated cycling sprints in soccer players. Journal of Strength & Conditioning Research, 25(7):1849-1856.

Brito, J., Vasconcellos, F., Oliveira, J., Krustrup, P., Rebelo, A. (2014). Short-term performance effects of three different low-volume strength-training programmes in college male soccer players. Journal of Human Kinetics, (40): 121-128.

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences (2nd ed.) New Jersey, NJ: Lawrence Erlbaum.

Crewther, B.T., Kilduff, L.P., Cook, C.J., Middleton, M.K., Bunce, P.J., Yang, G.Z (2011). The acute potentiating effects of back squats on athlete performance. Journal of Strength & Conditioning Research, 25(12): 3319-3325.

DeRenne, C. (2010). Effects of postactivation potentiation warm-up in male and female sport performances: a brief review. Strength & Conditioning Journal, 32: 58–64.

Docherty, D., Robbins, D., Hodgson, M. (2004). Complex training revisited: A review of its current status as a viable training approach. Strength & Conditioning Journal, 26(6): 52-57.

Doma, K., Sinclair, W.H., Hervert, S.R., Leicht, A.S. (2016). Postactivation potentiation of dynamic conditioning contractions on rowing sprint performance. Journal of Science and Medicine in Sport, 19(11): 951-956.

Ebben, W.P. (2002). Complex training: A brief review. Journal of Sports Science and Medicine, 1(2): 42-46.

Esformes, J.I., Bampouras, T.M. (2011). Effect of back squat depth on lower-body postactivation potentiation. Journal of Strength & Conditioning Research, 27(11): 2997–3000.

Hamada, T., Sale, D.G., MacDougall, J. D., Tarnopolsky, M.A. (2000). Postactivation potentiation, fiber type, and twitch contraction time in human knee extensor muscles. Journal of Applied Physiology, 88(6): 2131-2137.

Healy, R., Comyns, T.M. (2017). The Application of Postactivation Potentiation Methods to Improve Sprint Speed. Strength & Conditioning Journal, 39(1): 1-9.

Jo, E., Judelson, D.A., Brown, L.E., Coburn, J.W., Dabbs, N.C. (2010). Influence of recovery duration after a potentiating stimulus on muscular power in recreationally trained individuals. Journal of Strength & Conditioning Research, 24(2): 343–347.

Low, D., Harsley, P., Shaw, M., Peart, D. (2015). The effect of heavy resistance exercise on repeated sprint performance in youth athletes. Journal of Sports Sciences, 33(10):1028-34.

McBride, J.M., Nimphius, S., Erickson, T.M. (2005). The acute effects of heavy-load squats and loaded countermovement jumps on sprint performance. Journal of Strength & Conditioning Research, 19(4): 893-897.

Maio Alves, J.M., Rebelo, A.N., Abrantes, C., Sampaio, J. (2010). Short-term effects of complex and contrast training in soccer players' vertical jump, sprint, and agility abilities. Journal of Strength & Conditioning Research, 24(4): 936-41.

Mola, J.N., Bruce-Low, S.S., Burnet, S.J. (2014). Optimal recovery time for postactivation potentiation in professional soccer players. Journal of Strength & Conditioning Research, 28(6): 1529–1537.

Mohr, M., Krustrup, P., Bangsbo, J. (2003). Match performance of high-standard soccer players with special reference to development of fatigue. Journal of Sports Sciences, 21(7): 519-528.

Newman, M.A. Tarpenning, K.M., Marino, F.E. (2004). Relationship between isokinetic knee strength, single-sprint performance, and repeated-sprint ability in football players. Journal of Strength and Conditioning Research, 18(4): 867-872.

Ountzoudi, T.H., Manou, V., Dalamitros, A., Vavritsas, G., Kellis, S. (2014). The Effects of a Complex Training Protocol, with Strength and Power Preactivation Stimulus, on Sprint Running in Adolescent Sprinters. Inquiries in Sport & Physical Education, 1(3): 1-7.

Rahimi, R. (2007). The acute effects of heavy versus light-load squats in sprint performance. Physical Education & Sport, 5: 163-169.

Ramírez-Campillo, R., Vergara-Pedreros, M., Henríquez-Olguín, C., Martínez-Salazar, C., Alvarez, C., … Izquierdo, M. (2016). Effects of plyometric training on maximal-intensity exercise and endurance in male and female soccer players. Journal of Sports Science, 34(8): 687-93.

Robbins, D.W., Docherty, D. (2005). Effect of loading on enhancement of power performance over three consecutive trials. Journal of Strength & Conditioning Research, 19(4): 898-902.

Sarramian, V.G., Turner, A.N., Greenhalgh, A.K. (2015). Effect of postactivation potentiation on fifty-meter freestyle in national swimmers. Journal of Strength & Conditioning Research, 29(4): 1003–1009.

Seitz, L.B., Haff, G.G. (2015). Factors Modulating Post-Activation Potentiation of Jump, Sprint, Throw, and Upper-Body Ballistic Performances: A Systematic Review with Meta-Analysis. Sports Medicine, 46(2): 231-240.

Seitz, L.B., Villarreal, E.S., Haff, G.G. (2014). The temporal profile of postactiva-

tion potentiation is related to strength level. Journal of Strength & Conditioning Research, 28(3): 706–715.
Tillin, N.A., Bishop, D. (2009). Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. Sports Medicine, 39(2): 147-166.
Tsimachidis, C., Patikas, D., Galazoulas, C., Bassa, E., Kotzamanidis, C. (2013). The post-activation potentiation effect on sprint performance after combined resistance/sprint training in junior basketball players. Journal of Sports Science, 31(10): 1117-24.
Wilson, J.M., Duncan, N.M., Marin, P.J., Brown, L.E., Loenneke, J.P., Wilson, S.M., Jo, E., Lowery, R.P., Ugrinowitsch, C. (2013). Meta-Analysis of post activation potentiation and power: Effects of conditioning activity, volume, gender, rest periods, and training status. Journal of Strength & Conditioning Research, 27(3): 854-859.
Wisløff, U., Castagna, C., Helgerud, J., Jones, R., Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. British Journal of Sports Medicine, 38(3): 285-288.
Withers, R.T., Maricic, Z., Wasilewski, S., Kelly, L. (1982). Match analysis of Australian professional soccer players. Journal of Human Movement Studies, 8: 159-176.

Swedish tennis test: a field test to estimate maximal oxygen uptake in tennis players

Pierre-Marie Leprêtre[1], Philippe Lopes[2,3] and Pascal Sirvent[4]

Introduction

Tennis is a very complex sport, involving strength, power, speed, agility and explosiveness, as well as endurance components [Filipčič and Filipčič 2006, Baiget et al. 2015]. Particularly with respect to the duration of the tournaments and the length of the matches, a good aerobic capacity could positively influence the outcome of games [König et al. 2001]. Game analysis suggested that tennis matches intensity would correspond to a high intensity intermittent exercise [Mendez-Villanueva et al. 2007, Smekal et al. 2001] and data from most studies examining power recovery and maximal oxygen uptake ($\dot{V}O_2$max) suggest that a higher value of this variable results in improved recovery when performing repeated bouts of high intensity intermittent exercise [Tomlin and Wenger 2001]. Finally, based on the postulate that phosphocreatine resynthesis is controlled by aerobic metabolism, it is suggested that the faster its recovery rate might be attributed to a greater aerobic capacity [Yoshida T. 2002]. These findings support the idea that high $\dot{V}O_2$max values would constitute an important factor for tennis player's success.

Classically, a ramp test performed on motorized treadmill or on field track test could be used to directly or indirectly determine $\dot{V}O_2$max. A more specific test, the tennis specific fitness test, has been proposed to estimate aerobic fitness in tennis players [Girard et al. 2006]. Based on a personal game analysis, these authors proposed an intermittent progressive shuttle test with feigned strokes and randomized frontal and sagittal displacements spaced by passive recovery. When comparing the physiological responses after a progressive treadmill exercise test and

---

1. Laboratoire de recherche Adaptations Physiologiques à l'Exercice et Réadaptation à l'Effort, EA-3300, UFR-STAPS, Université de Picardie Jules Verne, Amiens, France.
2. UFR Sciences Fondamentales Appliquées, Département STAPS, Université d'Evry-Val-d'Essonne, Evry, France.
3. INSERM, UMR-S 1124, Sorbonne Paris Cité, Faculté des Sciences Fondamentales et Biomédicales, Université Paris Descartes, Paris, France.
4. Laboratoire de Biologie des Activités Physiques et Sportives, EA-3533, UFR-STAPS, Université Blaise Pascal – Clermont-Ferrand, Aubière, France.

following a tennis specific fitness test, $\dot{V}O_2max$ was found higher with the tennis specific fitness test suggesting that the motorized treadmill test failed to discriminate the respective part of artificial strokes and the ability to change direction. Finally, authors did not conclude about the interchangeability of tennis specific fitness and motorized treadmill tests.

In the past, validity of maximal multistage 20 m shuttle run test was established to predict $\dot{V}O_2max$ in adults [Léger et al. 1988, Ahmaidi et al. 1992, Berthoin et al. 1996]. The comparison of lower limbs and upper-lower limbs tests, both with changes of direction, might better advance the influence of upper limbs activity on the whole exercise $\dot{V}O_2$ response. Fargeas-Gluck and Léger (2012) and Brechbuhl et al. (2016) compared the cardiovascular responses measured during the maximal multistage 20 m shuttle run test with those obtained during a tennis specific test. However, as in the protocol proposed by Baiget et al. (2014), these two studies are only based on lateral movements from baseline, without the back and forth or diagonal trajectories normally present in an ecological playing situation [Filipčič and Filipčič 2006]. In addition, these tests [Fargeas-Gluck and Léger, 2012, Baiget et al. 2014, Brechbuhl et al. 2016], with real ball strikes with designated return areas, would alter both the cardiorespiratory responses [Ando et al. 2016] and the appropriate execution [Brechbuhl et al. 2017].

As increasing the complexity of the task by introducing real strikes would also be detrimental to a practical evaluation that should be quick and easy to implement in the field (one experimenter and one half-field) and to the reliability of measurement depending on player's level of expertise [Wengaard et al. 2017], we aimed to compare $\dot{V}O_2$ responses during the maximal multistage 20 m shuttle run test and the Swedish tennis tests, the latter being a modified version of tennis specific fitness test. We supposed that $\dot{V}O_2max$ is not markedly elevated during combined upper-lower limbs (Swedish tennis test) compared to lower limbs exercise (maximal multistage 20 m shuttle run test).

Methods

Subjects

Eight recreational male tennis players (third level French national tennis ranking) participated in the current study and all were healthy and free of cardiac and pulmonary disease. Their physical characteristics (mean ± SD) were: 26.0 ± 5.7 years, 184.4 ± 6.7 cm and 81.7 ± 10.7 kg. Each subject was familiarised to the experimental procedures and was informed of the risks and stresses associated with the protocol. Subjects gave their written informed consent in accordance with the guidelines of the University of Clermont-Ferrand.

Protocol

On separated days, all subjects performed two incremental exercise tests on an indoor hard tennis court (20.3°C of temperature, 35.0% of relative humidity and 762 mmHg of atmospheric pressure) 2-3 h after breakfast.

Regarding the maximal multistage 20 m shuttle run test, after a 2 min warm-up at 8.0 $km.h^{-1}$, each subject ran back and forth continuously between two points separated by 20 m apart. The runs were synchronized with beeps emitted from a pre-recorded tape. The subjects were forced to increase their speed since the interval between each successive beep decreased over the course of the test (0.5 $km.h^{-1}$ speed increase every 1 min until exhaustion for a total exercise duration not exceeding 25 min; Léger and Gadoury, 1989).

The Swedish tennis test is a continuous progressive exercise test performed with a tennis racquet in which subjects repeat displacements replicating the game of tennis (back and forth, and sideways). Each stage consists of shuttle runs, performed from a central base to one of six targets located around the court [Filipčič and Filipčič 2006] (figure 1). The sets of displacements included two forward (offensive), two lateral (neutral) and two backward (defensive) courses. When subjects arrived at the target, they were instructed to realize a powerful ball strike with their racquet (three forehands and three backhands, respectively) before moving back to baseline after each set. The initial running work rate was 1.67 $m.s^{-1}$ (i.e. 6.0 $km.h^{-1}$) lasting 1 min, then run shuttles progressively increased by 0.07 $m.s^{-1}$ (i.e. 0.25 $km.h^{-1}$) every 1 min until voluntary exhaustion or the incapacity of subject to attain target in time or to perform strokes with an acceptable technique. Movement velocities and directions were controlled by visual and sound feedback from a PC. Velocities and displacements were calculated from data collected during official competitions [Botton et al. 2011].

Data collection procedures

Breathing frequency (RF), tidal volume (V_T), minute ventilation ($\dot{V}$), inspired $\dot{V}O_2$ and CO_2 fractions (FeO_2 and $FeCO_2$, respectively) were measured at rest and throughout exercise using Cosmed $K4b^2$ ambulatory systems [Duffield et al. 2004]. Then, $\dot{V}O_2$ and $\dot{V}CO_2$ values were estimated using the Haldane Equation. $K4b^2$ was calibrated according to the manufacturer's instruction manual, particularly using ambient air (20.9% $\dot{V}O_2$ and 0.03% CO_2) and calibration gas (16.0% $\dot{V}O_2$ and 5.0% CO_2). The calibration of the turbine flow meters was performed with a 3 L syringe. Expired gases were measured breath by breath and the Cosmed software was used to automatically eliminate ectopic values and average the data every 15 s and $\dot{V}O_{2max}$ was defined as previously proposed (Lepretre et al. 2008). In addition, heart rate (HR) was recorded beat-to-beat, averaged over each breath (S810, Polar, Kempele, Finland) and, finally, averaged every 15 s.

Statistical Methods

Descriptive statistics are expressed as means and standard deviations (SD). After the normality of the data was verified (Skewness and Kurtosis measures, Fisher-Snedecor F-test), the non-parametric Wilcoxon signed-rank test for paired data was used to compare the basal and maximal physiological values. The significance alpha level was set at $p<0.05$. The relationships between cardiopulmonary variables obtained during both tests were assessed using a spreadsheet [Hopkins 2000], particularly using linear regression to assess the agreement for both raw and log transformed data, providing measures of bias and its 95% confidence limits, as well as the Pearson's correlation coefficient (r) for measured variables.

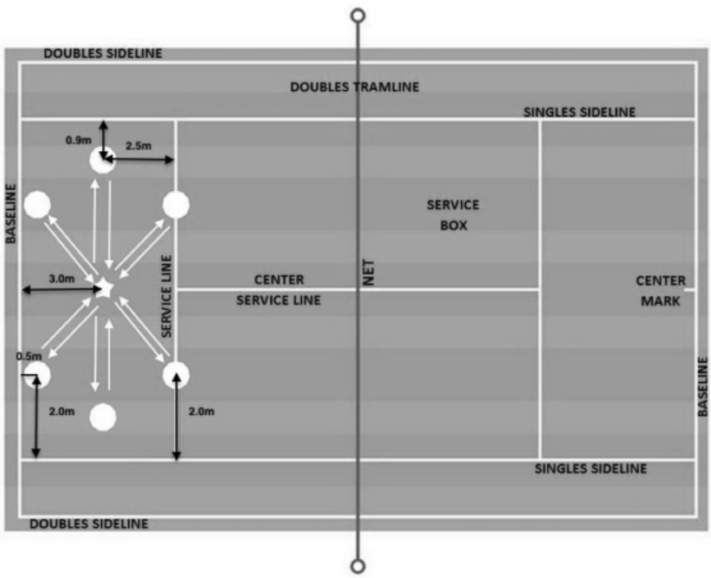


Figure 1. Court zones of the Swedish tennis test protocol.

Results

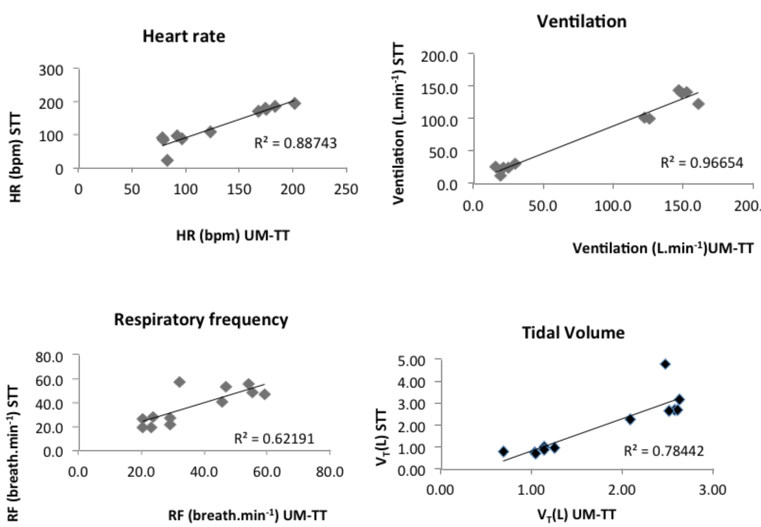
Time to exhaustion was longer during specific tennis test compared to the maximal multistage 20 m shuttle run test (15.5 ± 1.4 vs. 10.5 ± 0.5 min, p=0.043) with a large size effect (Cohen's d=0.93, effect-size correlation = 0.42). Table 1 presents the physiological variables measured at rest and during the maximal multistage 20 m shuttle run and Swedish tennis tests. Basal and maximal HR values were not different, with a moderate size effect (Cohen's d=0.56, effect-size correlation = 0.27). Absolute and relative $\dot{V}O2$, RF and $\dot{V}_E$ did not differ at rest, with a small size effect for RF (Cohen's d=0.15, effect-size correlation = 0.08) and large one for other variables (Cohen's d ranged from 1.45 to 1.65 and effect-size correlation ranged from 0.59 to 0.65). V_T baseline and maximal values were different when comparing tests, with a large size effect (Cohen's d were 2.55 and 2.22, and effect-size correlations were 0.79 and 0.74, respectively). Consequently, maximal $\dot{V}_E$ was higher during the maximal multistage 20 m shuttle run test comparing to the Swedish tennis test (with a large size effect (Cohen's d=2.33 and effect-size correlation = 0.76). Absolute and relative $\dot{V}O2max$ obtained during maximal multistage 20 m shuttle run test was also higher compared to the Swedish tennis test with a large size effect (Cohen's d=2.4 and effect-size correlation = 0.77).

Pearson correlation analysis indicated relevant relationships between physiological variables between tests: HR (r=0.94, p<0.05), absolute and relative $\dot{V}O2$ (r=0.98, p<0.01), $\dot{V}_E$ (r=0.98, p<0.01), RF (r=0.79, p<0.05) and $\dot{V}_T$ (r=0.89; p<0.05) (figure 2). Mean, upper and lower limits of bias were: absolute $\dot{V}O2$, 0.3 (equivalent to 3.8%) ranging from 0.1 to 1.0 L.min-1; relative $\dot{V}O2$, 4.1 (i.e. 3.3%), ranging from 2.2 to 12.7 mL.min$_{-1}$.kg$_{-1}$; VE , 8.3 L.min$_{-1}$ (i.e. 3.6 %), ranging from 1.3 to 19.9 L.min$_{-1}$; RF, 0.9 breaths. min$_{-1}$ (i.e. 2.2 %), ranging from 3.1 to 5.8 breaths.min-1 and $\dot{V}_T$, 0.2 L (i.e. 1.3 %) ranging from 0.3 to 1.6 L. For a mean bias of 3.3%, the true error of $\dot{V}O2$ measurement was likely to be substantially greater for maximal multistage 20 m shuttle run test compared to Swedish tennis test.

	Resting values		Maximal values	
	UM-TT	Swedish tennis test	UM-TT	Swedish tennis test
O_2 (L.min^{-1})	0.7 ± 0.1	0.9 ± 0.1	4.7 ± 0.3	4.0 ± 0.3*
O_2 (mL.min^{-1}.kg^{-1})	9.3 ± 1.5	11.7 ± 1.8	59.9 ± 3.7	51.1 ± 2.8*
V_E (L.min^{-1})	21.3 ± 2.2	25.2 ± 2.7	142.9 ± 6.3	126.0 ± 8.1*
RF (breaths.min^{-1})	24.2 ± 1.6	23.9 ± 1.6	48.8 ± 3.9	50.9 ± 2.5
V_T (L)	0.9 ± 0.1	± 0.1*	4.1 ± 0.4	2.5 ± 0.1*
HR (bpm)	91.6 ± 6.9	82.0 ± 12.3	181.1 ± 4.8	182.6 ± 4.0

Table 1. Basal and maximal physiological values measured before and during both 20 m shuttle run and Swedish tennis test.

Note: UM-TT = maximal multistage 20 m shuttle run test, $\dot{V}O_2$ = oxygen uptake, $\dot{V}_E$ = ventilation, RF = respiratory frequency, V_T = tidal volume, HR = heart rate. * $p<0.05$.



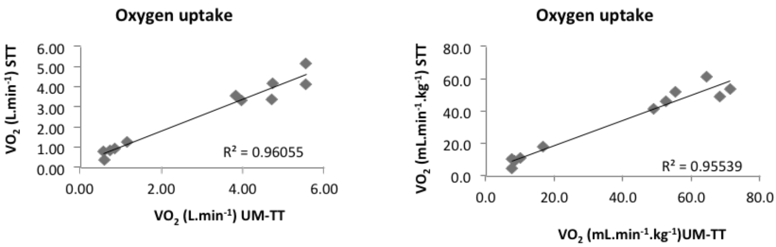


Figure 2. Regression diagrams regarding physiological variables in-between tests.

Note: UM-TT and SST corresponded to the maximal multistage 20 m shuttle run test and Swedish Tennis Test, respectively.

Discussion

Lasting from 1 to 5 h, a tennis match consists of repeated short and intense muscular actions, including fast running intercepted by longer periods of moderate and low intensity activity (Fernandez et al. 2006). It was observed that the aerobic energy expenditure was quite low over the game (49.4 ± 4.8% $\dot{V}O2max$) and that the maximal power during points was up to two or three times the $\dot{V}O2max$ (Botton et al. 2011). Thus, a tennis match is an intermittent anaerobic sport with an aerobic recovery phase (Fernandez et al. 2006). Using video analysis and indirect calorimetry, Botton et al. (2011) considered the anaerobic metabolism to be 32% of the total energy expenditure across the game, 67% for points and 95% for hitting the ball. However, the aerobic system plays a significant role in the maintenance of intensity level during a game, which is characterized by short activities bursts [Tomlin and Wenger 2001, Meckel et al. 2009]. Literature suggests that aerobic fitness enhances recovery from high intensity intermittent exercise through increased aerobic response, improve lactate removal and enhanced phosphocreatine regeneration [Tomlin and Wenger 2001]. The aim of this study was to compare $\dot{V}O2$ responses measured during maximal multistage 20 m shuttle run and Swedish tennis tests, with the main results showing good correlation in-between tests in the maximal HR and $\dot{V}O2$ values. This is consistent with previous observations that indicated that maximal values of cardiorespiratory variables were closely correlated when comparing specific tennis test and incremental treadmill protocols [Ferrauti et al. 2011] or maximal multistage 20 m shuttle run test [Fargeas-Gluck et Leger. 2012]. However, in the current study $\dot{V}O2max$ was markedly lower for the Swedish tennis test (combined upper-lower limbs exercise test) compared to the values obtained in the maximal multistage 20 m shuttle run test (lower limbs exercise only).

Previous studies showed that field tests significantly under-predicted the $\dot{V}$O2max compared to treadmill testing (Smekal et al. 1995, St Clair Gibson et al. 1998, Girard et al. 2006). A significant correlation between $\dot{V}$O2max determined by the maximal multistage 20-m shuttle run test and the highest $\dot{V}$O2 measured at the end of a previous tennis protocol was also shown (r=0.61; P<0.05) by St Clair Gibson et al. (1998). However, these authors attributed the less robust correlation between the shuttle run and motorized treadmill $\dot{V}$O2max tests to the tennis specific training (St Clair Gibson et al. 1998). In agreement with these previous studies, the highest $\dot{V}$O2 measured during Swedish tennis test was less compared to $\dot{V}$O2max. We also showed a good correlation between $\dot{V}$O2max measured during both the maximal multistage 20 m shuttle run test and Swedish tennis test. In the present study, a difference in minute ventilation was also found. Smekal et al. (2000) had already reported higher minute ventilation values in motorized treadmill test compared to field tests. However, recent studies did not show any difference in $\dot{V}$O2max or HR when comparing the specific tennis and maximal multistage 20 m shuttle run tests (Fargeas-Gluck et Leger. 2012, Brechbuhl et al. 2016), evidencing that specific tennis tests also allow reaching $\dot{V}$O2max and are useful for assessing aerobic fitness in this sport. Some methodological points (like expertise level and age) may explain this dissimilarity. In fact, Brechbuhl et al. (2016) were interested in assessing cardiorespiratory responses in highly trained competitive tennis players who were accustomed to changes of direction. The regular repetitions of changes of direction repetitions result in improved endothelial function and arterial blood vessel stiffness (Kruse Scheuermann, 2017) and, therefore, the oxygen muscle delivery in trained subjects. As a result, trained subjects can reach their $\dot{V}$O2max during tennis specific exercises involving changes in direction (Born et al. 2017). In contrast, acute changes of direction induce excessive over-stretching of the quadriceps and calf muscles (Kruse Scheuermann, 2017), which alter blood flow and subsequently oxygen availability and muscle utilization in our recreational players. Secondly, our subjects are older than the tennis players studied before (Fargeas-Gluck et Leger, 2012). Children rely more on oxidative metabolism and less on creatine kinase reaction to meet energy demand during exercise (Tomson et al., 2010), which is explained by a greater oxidative capacity, probably linked to a higher relative content in slow-twitch fibers before puberty. Hence, children solicited high $\dot{V}O2$ values during intense and exhaustive exercises, whatever the sport. Finally, differences in the displacements quality may have induced some specific cardiorespiratory responses, as oxygen transport to working skeletal muscles is challenged during whole-body exercise (Reybrouck et al. 1975). Muscle mass solicitation may explain the difference between $\dot{V}O2max$ measured during the maximal multistage 20 m shuttle run and Swedish tennis tests. In fact, Secher and Volianitis (2006) reported that the combined upper and lower limbs exercise induced a 10% decrease in lower limbs blood flow at a given work rate compared to lower limbs exercise alone. It has been reported that physical activities requiring repeated phases of high-force isometric and eccentric contractions resulted in restricted blood flow to the working muscle, thereby reducing oxygen delivery and increasing metabolite accumulation (Ferguson 2010). In consequence, there will be skeletal muscle fatigue, through both central and peripheral mechanisms, and a potential loss of motor control ultimately limiting performance. During Swedish tennis test, stretch-shortening cycle (Grezios et al. 2006) and eccentric wrist extensor muscular actions during simulated tennis stroke and displacements could potentially induce peripheral vasoconstriction and, therefore, compromise the ability to increase cardiac output and $\dot{V}O2$.

On the other hand, previous studies reported a protocol duration effect on the $\dot{V}O2max$ attainment. Buchfuhrer et al. (1983) have demonstrated that 8 to 17 min tests elicited higher values of $\dot{V}O2$ than shorter (<8 min) treadmill and cycle ergometer tests. In the current study, time to perform was longer to 8 min for both tests but the Swedish tennis test lasted longer than maximal multistage 20 m shuttle run test. Yoon et al. (2007) showed that healthy, moderately and highly trained men attained a higher $\dot{V}O2max$ when they were engaged in 8 rather than 16 min incremental test. Earlier, McCole et al. (2001) have reported that a 12 min incremental test elicited $\dot{V}O2max$ with a lower cardiac output compared with a 6 min one. Stage duration protocol may affect the stroke volume responses due to a different muscle mass recruitment (Lepretre et al. 2004) but also because of different cutaneous vasodilatation. McCole et al. (2001) supposed that twice longer duration test (12 vs. 6 min) would be responsible for the increase in core temperature eliciting cutaneous vasodilatation. Increased competition for the distribution of cardiac output can be made to the detriment of the highest $\dot{V}O2$ value achievement. Hence, Yoon et al. (2007) suggested that protocol duration of tests to $\dot{V}O2max$ should be between 8 and 10 min for moderately trained subjects.

Together, these data suggest that protocol duration might also explain a part of significant difference in higher $\dot{V}O_2$ value due to a different cardiac output challenge.

To conclude, our results indicate a strong relationship between the highest $\dot{V}O_2$ values measured during the Swedish tennis test and the 20 m shuttle run. However, the Swedish tennis test underestimated the $\dot{V}O_{2}max$ due to the specific motor action. Tennis training regimes should be adapted to the specific demands imposed by match-play. Sport-specific actions interact with the achievement of highest O_2 values, therefore, the Swedish tennis test rather than 20 m shuttle run should be used to evaluate the specific aerobic capacities of recreational male tennis players.

References

1. Ahmaidi S, Collomp K, Caillaud C, Préfaut C. Maximal and functional aerobic capacity as assessed by two graduated field methods in comparison to laboratory exercise testing in moderately trained subjects. Int J Sports Med. 1992 Apr;13(3):243-8.
2. Ando S, Komiyama T, Kokubu M, Sudo M, Kiyonaga A, Tanaka H, Higaki Y. Slowed response to peripheral visual stimuli during strenuous exercise. Physiol Behav. 2016 Jul 1;161:33-37.
3. Aziz AR, Chia MY, Teh KC. Measured maximal oxygen uptake in a multi-stage shuttle test and treadmill-run test in trained athletes. J Sports Med Phys Fitness. 2005 Sep;45(3):306-14.
4. Baiget E, Fernández-Fernández J, Iglesias X, Rodríguez FA. Tennis Play Intensity Distribution and Relation with Aerobic Fitness in Competitive Players. PLoS One. 2015 Jun 22;10(6):e0131304.
5. Baiget E, Fernández-Fernández J, Iglesias X, Vallejo L, Rodríguez FA. On-court endurance and performance testing in competitive male tennis players. J Strength Cond Res. 2014 Jan;28(1):256-64.
6. Berthoin S, Pelayo P, Lensel-Corbeil G, Robin H, Gerbeaux M. Comparison of maximal aerobic speed as assessed with laboratory and field measurements in moderately trained subjects. Int J Sports Med. 1996 Oct;17(7):525-9.
7. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet. 1986 Feb 8;1(8476):307-10.
8. Born DP, Kunz P, Sperlich B. Reliability and validity of an agility-like incremental exercise test with multidirectional change-of-direction movements in response to a visual stimulus. Physiol Rep. 2017 May;5(9). pii: e13275.
9. Botton F, Hautier C, Eclache JP. Energy expenditure during tennis play: a preliminary video analysis and metabolic model approach. J Strength Cond Res. 2011 Nov;25(11):3022-8.)
10. Brechbuhl C, Girard O, Millet GP, Schmitt L. On the Use of a Test to Exhaustion Specific to Tennis (TEST) with Ball Hitting by Elite Players. PLoS One. 2016 Apr 1;11(4):e0152389.

11. Brechbuhl C, Girard O, Millet GP, Schmitt L. Technical Alterations during an Incremental Field Test in Elite Male Tennis Players. Med Sci Sports Exerc. 2017 Sep;49(9):1917-1926.
12. Christmass MA, Richmond SE, Cable NT, Arthur PG, Hartmann PE. Exercise intensity and metabolic response in singles tennis. J Sports Sci. 1998 Nov;16(8):739-47.
13. Duffield R, Dawson B, Pinnington HC, Wong P. Accuracy and reliability of a Cosmed K4b2 portable gas analysis system. J Sci Med Sport. 2004 Mar;7(1):11-22..
14. Fargeas-Gluck MA, Léger LA. Comparison of two aerobic field tests in young tennis players. J Strength Cond Res. 2012 Nov;26(11):3036-42.
15. Ferguson RA. Limitations to performance during alpine skiing. Exp Physiol. 2010 Mar;95(3):404-10. Epub 2009 Nov 6.
16. Fernandez-Fernandez J, Mendez-Villanueva A, Fernandez-Garcia B, Terrados N. Match activity and physiological responses during a junior female singles tennis tournament. Br J Sports Med. 2007 Nov;41(11):711-6. Epub 2007 Jun 11.
17. Fernandez J, Mendez-Villanueva A, Pluim BM. Intensity of tennis match play. Br J Sports Med. 2006 May;40(5):387-91; discussion 391.
18. Ferrauti A, Kinner V, Fernandez-Fernandez J. The Hit & Turn Tennis Test: an acoustically controlled endurance test for tennis players. J Sports Sci. 2011 Mar;29(5):485-94.
19. Filipčič A, Filipčič T. Analysis of time and game characteristics in top profile tennis Acta Universitatis Carolinae. Kinanthropologica, 2006 Jan;42(1), 41-53.
20. Flouris AD, Metsios GS, Famisis K, Geladas N, Koutedakis Y. Prediction of VO2max from a new field test based on portable indirect calorimetry. J Sci Med Sport. 2010 Jan;13(1):70-3. Epub 2009 Jun 27.
21. Girard O, Chevalier R, Leveque F, Micallef JP, Millet GP. Specific incremental field test for aerobic fitness in tennis. Br J Sports Med. 2006 Sep;40(9):791-6. Epub 2006 Jul 19.
22. Katić R, Milat S, Zagorac N, Durović N. Impact of game elements on tennis match outcome in Wimbledon and Roland Garros 2009. Coll Antropol. 2011 Jun;35(2):341-6.
23. König D, Huonker M, Schmid A, Halle M, Berg A, Keul J. Cardiovascular, metabolic, and hormonal parameters in professional tennis players. Med Sci Sports Exerc. 2001 Apr;33(4):654-8.
24. Kruse NT, Scheuermann BW. Cardiovascular Responses to Skeletal Muscle Stretching: “Stretching” the Truth or a New Exercise Paradigm for Cardiovascular Medicine? Sports Med. 2017 Dec;47(12):2507-2520.
25. Léger L, Boucher R. An indirect continuous running multistage field test: the Université de Montréal track test. Can J Appl Sport Sci. 1980 Jun;5(2):77-84.
26. Léger L, Gadoury C. Validity of the 20 m shuttle run test with 1 min stages to predict VO2max in adults. Can J Sport Sci. 1989 Mar;14(1):21-6.
27. Léger LA, Lambert J. A maximal multistage 20-m shuttle run test to predict VO2max. Eur J Appl Physiol Occup Physiol. 1982;49(1):1-12.
28. Lepretre PM, Lopes P, Koralsztein JP, Billat V. Fatigue responses in exercise

under control of VO2. Int J Sports Med. 2008 Mar;29(3):199-205. Epub 2007 Sep 18.
29. Lepretre PM, Koralsztein JP, Billat VL. Effect of exercise intensity on relationship between VO2max and cardiac output. Med Sci Sports Exerc. 2004 Aug;36(8):1357-63.
30. Meckel Y, Machnai O, Eliakim A. Relationship among repeated sprint tests, aerobic fitness, and anaerobic fitness in elite adolescent soccer players. J Strength Cond Res. 2009 Jan;23(1):163-9.
31. Mendez-Villanueva A, Fernandez-Fernandez J, Bishop D, Fernandez-Garcia B, Terrados N. Activity patterns, blood lactate concentrations and ratings of perceived exertion during a professional singles tennis tournament. Br J Sports Med. 2007 May;41(5):296-300; discussion 300. Epub 2007 Jan 19.
32. Mendez-Villanueva A, Fernandez-Fernández J, Bishop D, Fernandez-Garcia B. Ratings of perceived exertion-lactate association during actual singles tennis match play. J Strength Cond Res. 2010 Jan;24(1):165-70.
33. Novas AM, Rowbottom DG, Jenkins DG. A practical method of estimating energy expenditure during tennis play. J Sci Med Sport. 2003 Mar;6(1):40-50.
34. Reid M, Crespo M, Lay B, Berry J. Skill acquisition in tennis: research and current practice. J Sci Med Sport. 2007 Feb;10(1):1-10. Epub 2006 Jun 30.
35. Reybrouck T, Heigenhauser GF, Faulkner JA. Limitations to maximum oxygen uptake in arms, leg, and combined arm-leg ergometry. J Appl Physiol. 1975 May;38(5):774-9.
36. Secher NH, Volianitis S. Are the arms and legs in competition for cardiac output? Med Sci Sports Exerc. 2006 Oct;38(10):1797-803. Review.
37. Smekal G, Baron R, Pokan R, Dirninger K, Bachl N. Metabolic and cardiorespiratory reactions in tennis-players in laboratory testing and under sport-specific conditions. Wien Med Wochenschr. 1995;145(22):611-5.
38. Smekal G, Pokan R, von Duvillard SP, Baron R, Tschan H, Bachl N. Comparison of laboratory and "on-court" endurance testing in tennis. Int J Sports Med. 2000 May;21(4):242-9.
39. Smekal G, von Duvillard SP, Rihacek C, Pokan R, Hofmann P, Baron R, Tschan H, Bachl N. A physiological profile of tennis match play. Med Sci Sports Exerc. 2001 Jun;33(6):999-1005.
40. Smekal G, von Duvillard SP, Rihacek C, Pokan R, Hofmann P, Baron R, Tschan H, Bachl N. A physiological profile of tennis match play. Med Sci Sports Exerc. 2001 Jun;33(6):999-1005.
41. St Clair Gibson A, Broomhead S, Lambert MI, Hawley JA. Prediction of maximal oxygen uptake from a 20-m shuttle run as measured directly in runners and squash players. J Sports Sci. 1998 May;16(4):331-5.
42. Tomlin DL, Wenger HA. The relationship between aerobic fitness and recovery from high intensity intermittent exercise. Sports Med. 2001;31(1):1-11.
43. Yoon BK, Kravitz L, Robergs R. VO2max, protocol duration, and the VO2 plateau. Med Sci Sports Exerc. 2007 Jul;39(7):1186-92.
44. Yoshida T. The rate of phosphocreatine hydrolysis and resynthesis in exercising muscle in humans using 31P-MRS. J Physiol Anthropol Appl Human Sci. 2002 Sep;21(5):247-55.

45. Hopkins WG (2000). Analysis of validity by linear regression (Excel spreadsheet). In: A new view of statistics. sportsci.org: Internet Society for Sport Science, sportsci.org/resource/stats/xvalid.xls.
46. Tomlin DL, Wenger HA. The relationship between aerobic fitness and recovery from high intensity intermittent exercise. Sports Med. 2001;31(1):1-11.
47. Tonson A, Ratel S, Le Fur Y, Vilmen C, Cozzone PJ, Bendahan D. Muscle energetics changes throughout maturation: a quantitative 31P-MRS analysis. J Appl Physiol (1985) 2010 Dec; 109(6): 1769–1778.
48. Wengaard E, Kristoffersen M, Harris A, Gundersen H. Cardiorespiratory Fitness Is Associated with Selective Attention in Healthy Male High-School Students. Front Hum Neurosci. 2017 Jun 28;11:330.

How Down syndrome impacts on the athletes' sports performance?

Tânia Bastos[1,2], Ana Querido[3,4], Ariel Villagra[5], José Irineu Gorla[6], Ricardo J. Fernandes[1,7], Rui Corredeira[8]

Introduction

Sport is meaningful in the lives of many people, including those with Down syndrome (DS). Like any others, individuals with DS participate in sport for different reasons and, for some of them, the transition from recreational sport to intensive training and competition is a natural progression for testing personal limits and pursuing athletic dreams and goals.(1) Nevertheless, trained individuals with DS are still scarcely studied.(2,3) In fact, little is known about the impact of training and sports performance in this population.

Therefore, in this review paper we go beyond the literature about intellectual disability and, specifically target individuals with DS. We intend to provide an overview on the evolution of sports participation for athletes with DS, from a recreational and rehabilitation perspective to a competitive performance perspective. To do so we will present a retrospective examination of the most up to dated literature about the impact of exercise and sport in this population. In addition, we seek to demonstrate which proper assessment instruments are available to support the training-coaching process and consequently, to reach the performance goals in athletes with DS. This book chapter reviews the performance factors implicated on competitive standards for athletes with DS and the

1. Centre of Research, Education, Innovation and Intervention in Sport (CIFI2D), Faculty of Sport, University of Porto, Porto, Portugal.
2. Research Center in Sports Sciences, Health Sciences and Human Development, CIDESD, University Institute of Maia, ISMAI, Maia, Portugal.
3. Associação de Natação do Norte de Portugal (ANNP), Porto, Portugal.
4. Clube de Propaganda da Natação (CPN), Ermesinde, Portugal.
5. Department of Physical Education, Sport and Human Movement, Autonomous University of Madrid, Madrid, Spain.
6. Laboratory of Physical Evaluation in Adapted Sport and Exercise, Department of Studies Adapted Physical Education, Faculty of Physical Education, University of Campinas, Campinas, Brazil.
7. Porto Biomechanics Laboratory, University of Porto, Porto, Portugal.
8. Research Centre in Physical Activity, Health and Leisure (CIAFEL), Faculty of Sport, University of Porto, Porto, Portugal.

context of sports organizations in this field. Specifically, we want to bring to discussion the inclusion of athletes with DS in Paralympic Games. We also provide practical recommendations for coaches focusing on the enhancement of sports performance of athletes with DS.

Down syndrome definition and characteristics

Down syndrome also called Trisomy 21 is the most frequent chromosome condition with an estimated incidence ranging between 1 in 1,000 to 1 in 1,100 live births worldwide.(4) Generally, this genetic disorder is caused by a fully or partial supplementary 21 chromosome and can appear in three forms, namely Simple Trisomy 21, Translocation, and Mosaicism.(5) Due to this genetic information, individuals with DS have a specific phenotype gathering a unique combination of intellectual, physical and physiological characteristics. Individuals with DS have intellectual disability ranging from mild to severe and 70 to 75% of them exhibit an IQ of between 25 to 50.(6)

Individuals with DS have a classic body shape and morphology, described as shorter in stature and shorter limbs-to-torso ratio, muscle hypotonia and atlanto-axial instability,(7) scoliosis, several foot deformities (e.g., flatfoot, *hallux valgus*, overriding fifth toe),(8) flat face, eyes slanting up, irregular shaped ears and large tongue relative to the mouth.(4) It is also known that they frequently exhibit congenital heart conditions, hearing and ophthalmological impairments, gastrointestinal disorders, obstructive sleep apnea (related with smaller upper airways, midfacial hypoplasia, adenoid hypertrophy, lingual tonsillar hypertrophy), thyroid disease,(9) leukaemia, epilepsy, diabetes and Alzheimer's disease.(4)

Consequently, individuals with DS are different from their peers with intellectual disabilities but without DS at physical and physiological levels. Individuals with DS have low peak oxygen consumption (VO2peak) and consequently low cardiorespiratory fitness in comparison with individuals with intellectual disabilities but without DS.(10) Autonomic dysfunction, reduced ventilatory capacity and metabolic dysfunction are the three factors pointed to explain the poor aerobic capacities in this population.(8) Pitetti, Climstein, Mays, and Barrett (11) demonstrated that individuals with DS also have lower levels of isokinetic muscular strength compared with their peers with intellectual disability but without DS. They have lower bone density compared with those who have an intellectual disability.(12) Finally, body composition in this population is characterized by higher levels of fat mass, lower levels of fat-free mass, and a different fat and lean distribution.(13) Consequently, individuals with DS have an increased risk of obesity compared with individuals with intellectual disabilities without DS.(14)

State of art about exercise and sport in individuals with down syndrome

Although it is well known that exercise and sport have several benefits for those who engage in a regular and continuous practice, individuals with DS are generally classified as sedentary.(15) To understand the impact of exercise and sports training in this population, we provide an updated state of art about physical fitness and sport-specific skills proficiency of individuals participating in exercise training. Full papers published in English were searched from six major electronic databases, namely Scopus, Ebsco, Sportdiscus, Web of Science, Pubmed and B-on over the last 7 years (2010-2017).

Physical fitness programs

Regarding physical fitness programs, Boer and Moss (16) developed a comparative analysis about the effectiveness of continuous aerobic training (continuous cycling and walking at an intensity of 70-80% VO2max) and interval training (10-30s all out sprints with 90s of low intensity walking or cycling) in anthropometrical, physiological and functional parameters of adults with DS. The previously mentioned authors demonstrated that both types of training have positive effects on various assessed parameters, but interval training was more effective in the improvement of body weight and aerobic capacity. Aerobic training was also proven to be effective in the reduction of pro-inflammatory cytokines and acute phase proteins associated with metabolic syndrome and insulin resistance in obese women with DS.(17)

Specifically, walking activities programs provided improvements on grip strength,(18) muscle strength (i.e., hip extensor, hip flexor, knee extensor, knee flexors, hip abductors and ankle plantarflexor), agility performance (19) and moderate positive effects on waist circumference, weight and walking endurance.(20) Assisted cycling exercise improved fine manual dexterity (i.e., dominant and bimanual hands) in individuals with DS.(21) Hussein (22) found that strength training of lower limb muscles including hip, knee and ankle effectively enhances forced vital capacity and peak expiratory flow rate in children with DS. In the same line of research, improvements on the pulmonary functions (i.e., vital capacity, forced vital capacity, forced expiratory volume after 1 second and peak expiratory flow rate) of children with DS were also demonstrated after a rowing aerobic exercise regimen.(23)

Different authors (24,25) have shown that progressive resistance training can improve upper and lower limb muscle strength in young individuals with DS. Isokinetic training is also an effective training method to improve muscular strength and postural balance in children with DS.(26) Finally, a 21-week conditioning training programme combined with plyometric jumps had positive effects on the acquisition of bone mass (i.e., total and hip bone mineral content, and total lean mass) in young individuals with DS.(27) Similar results were reported after a 1-year physical training program in the bone mineral content of adolescents.(28)

Overall, literature has showed that individuals with DS can be engaged in physical exercise programs in a safe and effective way. There is a research trend regarding the assessment of fitness outcomes focusing in cardiovascular fitness, muscular strength, body composition and balance. Research includes individuals with DS with a broad age range (i.e., from early childhood to adulthood) and from both genders. Moreover, researchers discuss their findings considering the importance of exercise programs as a way to improve physical health status and the ability to perform daily activities. The impact of physical fitness outcomes in the lives of individuals with DS is related with the decrease of long-term effects on the pathophysiological consequences of this syndrome, with the improvement of work tasks performance (e.g., box stacking, pail carry), and the adoption of an active lifestyle. It is possible to conclude that research about the impact of physical fitness parameters in the sports performance of athletes with DS is almost none-existent.

Sports training programs

In a sport-specific approach, research also provides insights on how involvement in sports training programs can affect individuals with DS. In a mix approach to sport-games (i.e., athletics, handball, football, basketball or volleyball) and swimming at aerobic levels, young individuals with DS were able to improve their cardiorespiratory fitness (i.e., VO-2peak, ventilation and maximum slope).(29) Voznesenskiy, Rivera-Quinatoa, Bonilla-Yacelga, and Cedeno-Zamora (30) explored the impact of horse riding and reported improvements in gross motor function measures. Water exercises and swimming are also very popular interventions among individuals with DS. Casey and Emes (31) reported significant improvements on the respiratory aspects of speech in a group of adolescents enrolled in swim training. Systematic practice of swimming can also have beneficial effects in stabilizing posture and in achieving symmetrical static ability during movements in children with DS.(32)

Carter and Horvat (33) showed that a 10-weeks taekwondo training successfully improved lower body strength of individuals with DS. A dance program had positive effects on the static balance with improvements related with the use of visual input associated to centre of pressure (closed and open eyes) being reported.(34) In a combined intervention based on dance and gymnastic exercises, children with DS improved flexibility and muscle elasticity, force and balance.(35)

In general, the analysis of sports training programs for individuals with DS clearly emphasizes the lack of research aiming to understand the specific-sports potential of athletes. Several studies were developed within a rehabilitation or physical therapy perspective meeting recommended guidelines for health benefits. Limited sports training and competition interventions assessed physical, technical or tactical sport-specific skills needed in a sport performance context. To our knowledge, only a small group of researchers in the field of swimming contrast with this research trend. Next, we provide detail information about the advances on research about performance factors in swimmers with DS.

Performance factors in swimming

One important issue in swimming research with athletes with DS is the characterization of upper limbs coordination factors implied in the different swimming techniques. Querido et al. (36) characterized the index of arm coordination (i.e., time between propulsive phases of the right and left upper limbs) in front crawl and backstroke and discussed the possible impact of DS features (i.e., lower muscular strength, higher body fat mass and anthropometric traits) in the swimmers inter upper limbs coordination. The relative duration of each upper limbs cycle phase, in addition with relative duration of propulsive and non-propulsive phases were also assessed. Results demonstrated that in both alternated techniques, all swimmers exhibited a catch-up mode coordination and negative index of coordination values. Hand lag time scores were far above comparing with those of elite swimmers without disabilities.

In front crawl significant positive correlations were found between this variable and the push phase as well as the propulsive phase. An inverse correlation was found between IdC and the non-propulsive phase. In backstroke, there was an inverse relationship between IdC and velocity. Querido et al. (36) argued that although swimmers with international experience were assessed in this study, athletes were not able to adapt their upper limbs coordination as usually occurs in swimmers with higher level of proficiency. This may suggest the presence of technical faults or physical shortcomings (e.g., higher hand lag time). Finally, the authors recommended the use of the index of coordination as an important tool to improve the coaches' knowledge on underwater cycle phases (i.e., augmenting the propulsive phases of the upper limbs and, with this, diminishing the lag time) and to identify technical mistakes.

In an even more detailed analysis on front crawl swimming technique, Querido et al. (37) assessed velocity, intra-cyclic velocity fluctuation, index of coordination, propelling efficiency and general stroking parameters in a sample of six international level athletes with DS. The authors reported a poorer performance on velocity, stroke rate, stroke length, index of coordination and propelling efficiency of the participants comparing to the reference scores available in literature for swimmers without disabilities. Moreover, it was reported a negative index of coordination (i.e., catch-up coordination mode) and higher intra-cyclic velocity fluctuation comparing with swimmers with DS. In contrast, swimmers with DS exhibited a direct relationship between velocity and stroke length and between index of coordination and stroke rate, which is in accordance with the literature for swimmers without disabilities. Overall results support the perspective that swimmers with DS struggle to maintain continuous propulsive actions, and lower coordinative development and technical efficiency.

In a complementary analysis, Marques-Aleixo et al. (38) examined the differences in intracycle velocity variation and upper limbs coordination in front crawl in swimmers with DS in three breathing conditions (i.e., without breathing, breathing to the preferred side, and breathing to the nonpreferred side). The main results showed that swimming velocity was higher without breathing and intracyclic velocity variation was higher while breathing. Swimmers tended to a catch up upper limbs coordination mode for both breathing conditions and a superposition mode when not breathing. Once again, research emphasis difficulties in upper limbs coordination that negatively impacts swimming performance in athletes with DS. Ulate and Campos (39) explored the effects of a 10-weeks weight resistance training on strength in swimmers with DS and reported significantly improvements in the maximum strength of pectoral muscles, dorsal muscles, femoral biceps, quadriceps, and triceps. After a 2-weeks follow-up, these improvements were maintained with no significant changes.

Lastly, the importance of swimmers with DS being able to follow a race strategy has also been approached in the literature.(40) It was suggested that visual pacer is an interesting instrument for swimming training providing swimmers with visual feedback about the cadence techniques (pacing) and allowing a self-evaluation of the performance. The authors reported that swimmers were not able to take advantage of short term visual feedback to maintain a pacing strategy. Initially, swimmers were not able to repeat the pace when feedback was removed and as target speed increased they moved from over estimation (i.e., too fast) to underestimation (i.e., too slow). This indicates that the swimmers were able to use the feedback but needed more practice. It is possible to conclude that coaches should systematically use pacer lights system in training and competition settings to improve the race performance in swimmers with DS.(40)

All the above-mentioned studies represent an innovative and original approach to deepen the knowledge about the performance factors in swimmers with DS. This because these evidences are the first attempts to describe the swimming technique of athletes with DS using several biomechanical related parameters. Overall, it is possible to conclude that elite swimmers with DS with extensive training and competition might experience disadvantaged in several performance parameters (e.g., swimming speed, propulsion, resistance, hydrodynamic drag).

Proper instruments to assess individuals with down syndrome

The existence of valid and reliable instruments to assess the performance factors of athletes with DS is an important issue for research and practice. Coaches, athletes and practitioners in general can make substantial improvements in the intervention methodologies both in training and competition settings and, therefore, enhance the sports-skills ability and the athletic performance. Nevertheless, the lack of appropriate instruments for measuring the different performance factors of athletes with DS remains a problem. This because it is well-known that many instruments used with the general population are not valid and reliable to apply to individuals with disabilities.

Therefore, to conduct quality research and overcome the above-mentioned issue, researchers cannot forget to explore the feasibility, validity and reliability of the tools they wish to apply on individuals with DS. Hereinafter, we present a critical analysis about the instruments that have been properly developed and available to be used in this population. Full papers published in English were searched from six major electronic databases, namely Scopus, Ebsco, Sportdiscus, Web of Science, Pubmed, and B-on over the last 7 years (2010-2017). Manual search of journals (e.g., Adapted Physical Activity Quarterly, European Journal of Adapted Physical Activity, Journal of Intellectual and Developmental Disability, Journal of Intellectual Disability Research) and scanning of reference lists to pick up any further studies missed by the electronic search were also conducted. These sources were chosen, because together, they provide a complete overview of research concerning DS, sports/physical activity and exercise. The combination of search terms employed included: Down syndrome/Trisomy 21, Intellectual Impairment/Intellectual Disability/Mental Retardation, Physical Activity, Sports, Performance, Training, Competition, Athletes, validation/validity, reliability and feasibility. Papers were excluded if they met the following exclusion criteria: i) not related to the scope; ii) papers included in the systematic review papers already selected and iii) mix sample of individuals with intellectual disabilities and DS.

Physical fitness

In a broader perspective about the validity and reliability of physical fitness field-based tests, it was conducted a systematic review to identify the available protocols to be use in the population with DS.(41) Matching with the inclusion criteria, several studies were identity related with aerobic resistance field test assessments (n=7), strength tests (n=5), balance tests (n=3), and agility tests (n=1). The authors stated that the half-mile run-walk (i.e., aerobic endurance), hand-held dynamometer (i.e., muscular strength) and the four-square balance tests (i.e., balance) seem to be the most valid tests. These findings are very helpful because these instruments are easy to administrate to a large number of participants with minimal costs.

Also contributing for the validation of fitness testes in adults with DS, Boer and Moss (42) explored the test-retest reliability and minimal detectable change in a group of balance (static balance – standing in one leg; dynamic balance – walking on a balance bean), flexibility (sit-and-reach; shoulder stretch), muscular strength and endurance (chair stand test; handgrip strength; modified curl-up-test; trunk lift; isometric push-up), aerobic (16-m modified shuttle-run test; 6-min walk test) and functional task (8-foot get-up-and-go test) tests. All tests demonstrated adequate feasibility and relative and absolute test–retest reliability in adults with DS. The authors highlighted the importance of their findings to monitor performance alterations over time and success of training interventions.

In a specific sub-group of cardiorespiratory fitness tests, the reliability and convergent validity of the 6 minutes run test was assessed. (43) A group of young adults with DS performed the 6-min run test and the 16-min shuttle run test twice with a one week-interval between test and retest. The results of this study indicate that the 6 minutes run test shows high test/retest reliability and moderate to moderately high convergent validity when performed by adults with DS. Boer and Moss (44) established criterion-related validity of the 16-metre PACER and six-minute walk distance tests to VO2peak as well as predictors of VO2peak in adults with DS. The authors concluded that both 16-metre PACER and six-minute walk distance are valid field tests for predicting aerobic capacity, showing moderate-to-strong coefficients of determination and correlation coefficients in adults with DS.

Aranha, Samuel, and Saxena (45) discussed the importance of having valid tests to assess balance (static and dynamic) in children with DS. In this sense, the authors estimate the reliability and sensitivity to change of the timed standing balance test (i.e., standing on a floor and standing on a foam pad) using the time required to maintain in four conditions (i.e., eyes open static, eyes closed static, eyes open dynamic, and eyes closed dynamic) and concluded that the timed standing balance test is an easy to administer test and sensitive to change with strong absolute and relative reliabilities. Therefore, this instrument is very useful to assess balance in children with DS in clinical practice but also in community-based interventions such as exercise programs. Similarly, Bandong, Madriaga, and Gorgon (46) proved the reliability and validity of the Four Square Step Test (i.e., ability to step in different directions) in this population.

Anthropometric measures

The development of an accurate method to assess body composition, in particular fat percentage (BF%), is an important research topic and substantial research has been conducted. Bandini, Fleming, Scampini, Gleason, and Must (47) determined the validity of body mass index (BMI) to identify excess fatness in youth with DS based on dual-energy X-ray absorptiometry (DXA) and Freedman's cut-offs. Overall, the obesity (≥95th percentile) cut-off performs better than the overweight cut-off (85–94th percentile) in identifying elevated fatness in adolescents with DS. The authors suggest that more research is needed to confirm the cut-off points on a larger population of individuals and to explore the association with adverse health outcomes.

Similarly, it was estimated the BMI cut-off point for the diagnosis of obesity in adolescents with DS according to different references for BMI classification in relation to the BF% measured by DXA.(48) The authors reported that the criteria that use the BMI for estimating obesity, as well as references based on specific curves for the population with DS are associated with BF% estimated by the DXA and concluded that the cut-off point of z-score above of 2.14 of the World Health Organization presented better specificity.

In the same line of research, Nascimento et al. (49) determined a predictive equation, calculated by DXA analysis, for BF% based on BMI for adolescents with DS. The authors demonstrated that BMI is an effective measure and provided an accurate equation to estimate BF% developed from BMI values. Likewise, Freire, Costa, and Gorla (50) also verified that the BMI exhibited a strong correlation with the BF% in children and adolescents with Down syndrome. However, in both previously mentioned studies it is highlighted the need to conduct future studies to confirm the reproducibility of the findings.

Using a similar research design, it was explored the agreement of BMI-based equations (tested 4 equations) and DXA in determining BF% but in a sample of adults with DS. (51) The results showed a substantial amount of inter method discrepancy and wide limits of agreement exist between BMI-BF% equations and DXA. Consequently, the authors suggested that BMI-based on BF% equations for estimating the level of BF% should not be used in individuals with DS. Although BMI is the best know and worldwide used method to determine body fat, it is possible to verify that findings of different studies in individuals with DS are not consensual.

In this sense, the validity of the body adiposity index for measuring BF% in adults with DS has also been explored.(52) The criterion for BF% was determined by DXA and predicted BF% was estimated by the body adiposity index method. The authors concluded that the use of the body adiposity index does not appear to be accurate for estimating BF% in individuals with DS. Loveday, Thompson, and Mitchell (53) also payed attention to the best method to determine the BF% in children with DS. However, the previously mentioned authors explored the accuracy of bioelectrical impedance using DXA validation and aimed to identify the existing algorithm best predicts BF% in the population with DS. The authors concluded that bioelectrical impedance can be used to accurately measure adiposity and the recommended the use of Schaeffer's algorithm for calculation of BF% in this population.

More recently, it was recommended the use of a predictive equation to estimate BF% from skinfolds (biceps, triceps, subscapular, supraspinale, abdominal, front thigh, and medial calf) in adolescents with DS.(54) However, Usera, Foley, and Yun (55) demonstrated that skinfolds and anthropometric girth measurements are not a feasible way to assess body composition and highlight the need to develop new equations specifically for in individuals with DS.

Physiological measures

Boer (56) explored the accuracy of the Fernhall's prediction equation for the determination of maximum heart rate in adults with DS using a maximal aerobic test and concluded that it was not accurate for the age range of his sample. It was suggested that more research is needed to develop different prediction equations for more specific age and body mass index categories for individuals with DS. On the other hand, Chen, Ringenbach, Snow, and Hunt (57) explored the validity of a pictorial rate of perceived exertion scale, based on heart rate index in a walking protocol, to monitor exercise intensity in young adults with DS. Results indicated significant positive relations between heart rate and rate of perceived exertion in most of the sample. The participants were able to perceive and report a subjective estimation of physical exertion, which was reflective of the change of heart rate. Therefore, the authors concluded that the rate of perceived exertion scale is useful to monitor exercise performance in adults with DS.

Agiovlasitis et al. (58) critically analysed the use of the American College of Sport Medicine equation to predict gross-VO2 during over-ground walking in individuals with DS. The results demonstrated that the American College of Sport Medicine formula under-estimated gross-VO2 across speeds showing altered curvilinear gross-VO2 to speed relationship. Consequently, the previously mentioned authors tested a new equation, specifically developed for individuals with DS, and demonstrated that this equation was accurate and could be used for prescribing over-ground walking intensities. These findings are important to establish appropriate exercise intensities, according to the participants' needs that will improve the quality of the exercise programs offered to individuals with DS.

Finally, Seron and Greguol (59) conducted a systematic review to determine the validity and reliability of protocols to assess VO2max in young individuals with DS. Matching with the inclusion criteria, the authors selected 18 tests, 14 measured the VO2peak in a laboratory and 4 were field tests. Concerning the tests performed in a laboratory, only 8 used validated protocols (i.e., treadmill and rowing) for individuals with DS. Of the field tests, only one was not validated. The authors concluded that most of the selected studies used maximal tests. A large number of studies used tests which had not been specifically validated for the evaluated population and a few number of studies used field tests to evaluate VO2.

Physical activity levels

To proper assess the physical activity levels of individuals with DS, researchers explored the accuracy of pedometers and accelerometers in this population. Agiovlasitis, Beets, Lamberth, Pitetti, and Fernhall (60) examined the accuracy of a pedometer with a tri-axial accelerometer mechanism - Walk4life MVPa pedometer, in measuring steps at different walking speeds comparing individuals with and without DS. The authors demonstrated that this instrument measures steps with high accuracy at the preferred walking speed and at speeds ≥1.0 m s-1 in both groups of individuals. However, accuracy is compromised at slower speeds in the group with DS. The authors suggest that professionals can use with confidence the Walk4life MVPa pedometer for monitoring the steps at walking speeds ≥1.0 m s-1 in individuals with DS. Below 1.0 m s-1 walking speeds, the pedometer use is compromised.

A cross-validation and reliability study comparing two triaxial accelerometers (the SenseWear and RT3) to a criterion measure in young adults with DS concluded that both instruments can be used to monitor physical activity.(61) However, limitations were observed regarding the use of the accelerometers in energy expenditure estimates.

After an extensive and detailed analysis of the literature about the existence of valid and reliable instruments to assess individuals with DS it is possible to conclude that: i) this topic is in the agenda of the researchers and the vast majority of the studies were published very recently; ii) there is a research trend towards the exploration of physical fitness and anthropometric tests that require simple equipment, time-saving, and low cost administration; iii) most studies highlight the importance of valid and reliable tools to improve the design of lifestyle interventions (e.g., exercise), skills for daily life, and clinical practice; and iv) future research needs to replicate and confirm the present findings because in some cases outcomes from different studies are contrary.

Although most of the instruments previously mentioned can be used in a competitive sport context to assess athletes with DS, we could not identify any study developing validity or reliability procedures about instruments related with specific physical, technical or technical sport skills.

Sports organizations for athletes with down syndrome

From "Special Olympics" to "Sports Union for Athletes with Down syndrome"

Traditionally, individuals with DS had been included in sports organizations for individual with intellectual disabilities. In this context, Special Olympics International is a global non-profit sporting organization and the largest one (over 4.7 million athletes) serving individuals with developmental disabilities, including individuals with intellectual disabilities and DS.(62) The Special Olympics was originally founded in the United States of America in 1968 and is represented in 169 countries with a range of 35 individual and team sports. Special Olympics is well-known by the diversity of programs offered such as Motor Activity Training Program, Youth Athletes Program, Unified Sports, Sports Partnerships and Partner Clubs.

According to the Special Olympics,(62) its mission is to provide a year-round sports training and athletic competition in a variety of sports for children and adults with intellectual disabilities. The goal is to offer sport opportunities to develop physical fitness, demonstrate courage, experience joy and participate in a sharing of gifts, skills and friendship with their families, other athletes and the community. Benefits regarding the participation in Special Olympics programs are associated to the improvement self-esteem and self-confidence, social support and social acceptance, as well as, positive self-perceptions.(63) As such, elite performance is not the main focus of Special Olympic organization.

Since 1986, the International Federation for Intellectual Disability Sport (INAS) assumed the purpose of managing elite sport competition for athletes with intellectual disabilities worldwide, allowing athletes to achieve excellence in sport and high-level competition. INAS is represented in 80 countries with more than 300,000 athletes with intellectual disability participating in 14 sports. INAS is responsible for the Global Games (2004-2019), the world largest elite sport event for athletes with intellectual disabilities participating in athletics, swimming, table tennis, rowing, basketball, futsal, tennis, cycling and taekwondo.(64) This Federations is a member of the International Paralympic Committee (IPC) and in the last decades developed intensive collaborative work with the IPC in the field of the classification system to allow the re-entry of athletes with intellectual disability in London Paralympic Games.(65)

Over the edge of IPC-INAS, athletes with intellectual disabilities participated in the Atlanta (1996), Sydney (2000), London (2012) and Rio (2016) Paralympic Games. In Rio, athletes with intellectual disabilities participated in athletics, swimming and table tennis competitions.(64) Athletes with DS are eligible to compete in both INAS (i.e., Global Games) and IPC (i.e., Paralympic Games) competitions in the same category as the athletes with intellectual disability. The IPC advocates that athletes with DS must be included in a single disability category meeting the sport-specific criteria for athletes with intellectual disability. This because Paralympic classification system does not include categories for specific type of disability but only three major areas, namely physical, visual and intellectual impairment.(65)

Although classification rules include all athletes with an intellectual disability (athletes with DS included), as we have previously stated there are research evidences that athletes with DS are not able to reach the same performance standards that athletes with intellectual disabilities in an equal elite sports context. The specific combination of intellectual, physical and physiological features of DS seems to have a negative impact on high-level performance when compared with athletes with intellectual disabilities. For example, Smedley (66) argued that atlanto-axial instability and diving are crucial concerns for many swimmers struggling to meet the regulation for competitive swimming.

In addition, practical evidences also support this fact. For instance, we developed a detailed analysis of the swimming events results on the Global Games (2004, 2009, 2011 and 2015) and Paralympic Games (1996, 2000, 2012 and 2016) and we could not identify any swimmer with DS reaching a final phase, even less, being medalled. It seems that athletes with Down syndrome have been outclassed by athletes with intellectual disabilities without other associated comorbidities. Despite of, at the request of the 2013 INAS General Assembly and the membership to re-consider the traditional single ‘intellectual disability’, INAS has been considering the feasibility and benefits of introducing additional eligibility groups into competition programme, specifically for DS. In this sense, INAS is developing a pilot project, included in INAS Strategic Plan 2017-2020, to monitor and evaluate these new eligibility groups in next 2017 INAS World Table Tennis and Swimming Championships.(64)

In face of the previously mentioned challenges for athletes with DS, in 2012 a new sports Union was formed to support athletes with DS aiming to achieve the highest levels of sporting excellence, named Sports Union for Athletes with Down syndrome (SU-DW).(67) The SU-DW represents and co-ordinates 7 sports and organizations for individuals with DS, namely the International Athletics Association for athletes with Down Syndrome, the Down Syndrome International Swimming Organization, the Football International Federation for players with Down Syndrome, the Down Syndrome International Gymnastics Organization, the International Table Tennis Association for players with Down Syndrome, the Judo for Down Syndrome players and the Skiing for people with Down Syndrome. In 2016, Italy, occurred the first World Trisome Games for all the sports represented by the SU-DW. The current mission of this organization is the recognition of a new class, specific for athletes with DS and apart from the intellectual disability classification, in Tokyo's Paralympic Games in 2020 by the Paralympic Committee.(67)

Practical recommendations for coaches and other practitioners

Having the above-mentioned rational in consideration, we suggest a group of practical recommendations to help coaches to enhance the performance of athletes with DS. The race or game analysis has been widely accepted in the scientific and coaching community to understand the athlete's behaviour in competition. However, little has been done at international events for DS athletes. Coaches should look up for this kind of approach and, although methodological issues make it difficult to compare different studies, videotaping their athletes in competition allows the coaches to, at least, analyse and observe behaviour and performance in different competitions.

Athletes with DS seem to improve their physical fitness, however, their anthropometric characteristics, lack of strength and reduced cardiovascular capacity, when compared to athletes without disability or athletes with intellectual disability, seems to impact on their sports performance. Nevertheless, we emphasize the idea that competitive sports practice may help individuals attaining a better physical fitness profile. Therefore, coaches should enable physical fitness training and promote activities directed towards performance.

Coaches must find training strategies to promote their understanding of the technical gesture as well as the race or game strategy (e.g., videos, manipulation, filming and after analysis). It is also important to establish realistic goals in accordance with the athletes (i.e., make them part of the process). As part of a team, coaches should also promote opportunities for athletes with DS to interact with all the persons from the Club (e.g., teammates, other coaches, directors), with or without disability, creating some tasks or games together. It is also our belief that, at some points of the season, coaches should enable their athletes to have different experiences and do other things together such as try other sports, have lunch or dinner together and go to the movies.

Conclusions

In general, this review putted in evidence the need to improve knowledge about physical fitness, technical and technical sport-specific skills influencing the performance of athletes with DS. Exception was made for the swimming area where it was possible to identify a small but consistent body of research about the biomechanical factors influencing swimming performance. Moreover, there is an absence of studies about research methodologies and, specifically, assessment tools valid and reliable to apply in both training in competition settings. It is crucial that more research on athletes with DS is available, particularly for coaches to use the information in the training process across different sports and from a range of scientific disciplines (e.g., technical, biomechanical, physiological, psychological variables or nutritional practices).

Trends in the results highlighted the importance of exercise to improve the efficiency in performing everyday activities (e.g., workplace activities) that typically emphasise physical skills. Exercise is valued due to its impact on reducing the potential health risks associated with low fitness and sedentary behaviour, on maintaining an active lifestyle, on improving functional independence and quality of life in individuals with DS.

Lastly, athletes with DS struggle to be recognized as athletes on a single and specific competition class or category. This a very hot topic related with the inclusion of athletes with DS in Paralympic Games. Nowadays there are intensive discussions about athletes with DS eligibility criteria that we believe will have an impact on the sports regulations of the major sports organizations for individuals with disabilities.

References

1. Van de Vliet P, Rintala P, Frojd K, Verellen J, Van Houtte S, Daly DJ, et al. Physical fitness profile of elite athletes with intellectual disability. Scand J Med Sci Sports. 2006;16(6):417-425. doi: 10.1111/j.1600-0838.2006.00539.x.
2. Balic M, Mateos E, Blasco C, Fernhall B. Physical fitness levels of physically active and sedentary adults with Down syndrome. Adapt Phys Activ Q. 2000;17:310-321.
3. Perán S, Gil JL, Ruiz F, Fernandez-Pastor V. Development of physical re-

sponse after athletics training in adolescents with Down's syndrome. Scand J Med Sci Sports. 1997;7(5):283-288.
4. World Health Organization [Internet]. Genomic resource centre – Genes and Human disease. [cited 2017 May 19]. Available from http://www.who.int/genomics/public/geneticdiseases/en/index1.html
5. Bull MJ, Committee on Genetics. Clinical report – Health supervision for children with Down syndrome. Pediatrics. 2011;128(2):393-406. doi:10.1542/peds.2011-1605.
6. Vicari S. Motor development and neuropsychological patterns with Down syndrome. Behav Genet. 2006;36(3):355–364. doi: 10.1007/s10519-006-9057-8.
7. Myśliwiec A, Posłuszny A, Saulicz E, Doroniewicz I, Linek P, Wolny T, Knapik A, Rottermund J, Żmijewski P, Cieszczyk P. Atlanto-Axial Instability in People with Down's Syndrome and its Impact on the Ability to Perform Sports Activities – A Review. J Hum Kinet. 2015;48(1):17-24. doi: 10.1515/hukin-2015-0087.
8. Mansoura E, Yaacouba JJ, Bakounya Z, Assia A, Ghanema I. A podoscopic and descriptive study of foot deformities in patients with Down syndrome. Orthop Traumatol Surg Res. 2017;103(1):123–127. doi: 10.1016/j.otsr.2016.10.001.
9. Roizen NJ, Magyar CI, Kuschner ES, Sulkes SB, Druschel C, van Wijngaarden E, et al. A community cross-sectional survey of medical problems in 440 children with Down syndrome in New York State. J Pediatr. 2014;164(4):871–875. doi: 10.1016/j.jpeds.2013.11.032.
10. Pitetti K, Baynard T, Agiovlasitis S. Children and adolescents with Down syndrome: physical fitness and physical activity. J Sport Health Sci. 2013;2(1):47–57. doi: 10.1016/j.jshs.2012.10.004.
11. Pitetti KH, Climstein M, Mays MJ, Barrett PJ. Isocinetic arm and leg strength of adults with Down syndrome: A comparative study. Arch Phys Med Rehabil. 1992;73:847-850.
12. Geijer JR, Stanish HI, Draheim CC, Dengel DR. Bone Mineral Density in Adults With Down Syndrome, Intellectual Disability, and Nondisabled Adults. Am J Intellect Dev Disabil. 2014;119(2):107-114. doi: 10.1352/1944-7558-119.2.107.
13. Gonzalez-Agüero A, Ara I, Moreno LA, Vicente-Rodriguez G, Casajus JA. Fat and lean masses in youths with Down syndrome: gender differences. Res Dev Disabil. 2011;32(5):1685-1693. doi: 10.1016/j.ridd.2011.02.023.
14. Melville CA, Cooper SA, Morrison J, Allan L, Smiley E, Williamson A. The prevalence and determinants of obesity in adults with intellectual disabilities. J Appl Res Intellect Disabil. 2008;21(5):425–437. doi: 10.1111/j.1468-3148.2007.00412.x.
15. Izquierdo-Gomez R, Veiga OL, Villagra A, Diaz-Cueto, Up&Down Study Group. Correlates of sedentary behaviour in youths with Down syndrome: the UP&DOWN study. J Sports Sci. 2015;33(14)1-11. doi: 10.1080/02640414.2014.994660.
16. Boer PH, Moss SJ. Effect of continuous aerobic vs. interval training on selected anthropometrical, physiological and functional parameters of adults with Down syndrome. J Intellect Disabil Res. 2016;60(4):322-334. doi: 10.1111/jir.12251.
17. Ordonez FJ, Rosety MA, Camacho A, Rosety I, Diaz AJ, Fornieles G, Garcia

N, Rosety-Rodriguez M. Aerobic training improved low-grade inflammation in obese women with intellectual disability. J Intellect Disabil Res. 2014;58(6):583-590. doi: 10.1111/jir.12056

18. Chen C-C, Rigenbach DRS, Snow M. Treadmill walking effects on grip strength in young men with Down syndrome. Res Dev Disabil. 2014;35(2):288–293. doi: 10.1016/j.ridd.2013.10.032.
19. Lin H-C, Wuang Y-P. Strength and agility training in adolescents with Down syndrome: A randomized controlled trial. Res Dev Disabil. 2012;33(6):2236–2244. doi: 10.1016/j.ridd.2012.06.017.
20. Shields N, Taylor NF. The feasibility of a physical activity program for young adults with Down syndrome: A phase II randomised controlled trial. J Intellect Dev Disabil. 2015;40(2):115–125. doi: 10.3109/13668250.2015.1014027.
21. Chen C-C, Rigenbach SDR, Albert AR. Assisted Cycling Exercise Improves Fine Manual Dexterity in Persons with Down's syndrome. J Appl Res Intellect Disabil. 2014;27(3):264–272. doi:10.1111/jar.12061.
22. Hussein ZA. Strength training versus chest physical therapy on pulmonary functions in children with Down syndrome. Egypt J Med Hum Genet. 2017;18(1):35–39. doi: 10.1016/j.ejmhg.2016.02.008.
23. El Kafy EMA, Helal OF. Effect of rowing on pulmonary functions in children with Down syndrome. Pediatr Phys Ther. 2014;26(4):437-445. doi: 10.1097/PEP.0000000000000072.
24. Shields N, Taylor NF. A student-led progressive resistance training program increases lower limb muscle strength in adolescents with Down syndrome: A randomised controlled trial. J Physiother. 2010;56(3):187-193.
25. Shields N, Taylor NF, Wee E, Wollersheim D, O'Shea SD, Fernhall B. A community-based strength training programme increases muscle strength and physical activity in young people with Down syndrome: A randomised controlled trial. Res Dev Disabil. 2013;34(12):4385-4394. doi: 10.1016/j.ridd.2013.09.022.
26. Eid MA, Aly SM, Huneif MA, Ismail DK. Effect of isokinetic training on muscle strength and postural balance in children with Down's syndrome. Int J Rehabil Res. 2017;40(2):127-133. doi: 10.1097/MRR.0000000000000218.
27. González-Agüero A, Vicente-Rodríguez G, Gómez-Cabello A, Ara I, Moreno LA, Casajús JA. A 21-week bone deposition promoting exercise programme increases bone mass in young people with Down syndrome. Dev Med Child Neurol. 2012;54(6): 552-556. doi: 10.1111/j.1469-8749.2012.04262.x.
28. Ferry B, Gavris M, Tifrea C, Bembea M, Courteix D. The bone tissue of children and adolescents with Down syndrome is sensitive to mechanical stress in certain skeletal locations: A 1-year physical training program study. Res Dev Disabil. 2014;35(9):2077-2084. doi: 10.1016/j.ridd.2014.05.004.
29. Casajús JA, Pueyo D, Vicente-Rodríguez G, González-Agüero A. Improvements in cardiorespiratory fitness through aerobic training in young people with Down's syndrome: A longitudinal study. Apunts Med Esport. 2012;47(174):49-54. doi: 10.1016/j.apunts.2011.06.003.
30. Voznesenskiy S, Rivera-Quinatoa JA, Bonilla-Yacelga KA, Cedeno-Zamora MN. Do equine-assisted physical activities help to develop gross motor skills in children with the Down syndrome? Short-term results. Procedia Soc Behav Sci. 2016; 233:307-312. doi: 10.1016/j.sbspro.2016.10.140.

31. Casey AF, Emes C. The Effects of Swim Training on Respiratory Aspects of Speech Production in Adolescents With Down Syndrome. Adapt Phys Activ Q. 2011;28(4):326-341.
32. Popa C-E, Galeru O. Study regarding the improvement of postural control in children who have Down syndrome through swimming. Gymn - Sci J Educ Sports Health. 2012;13(2):85-98.
33. Carter K, Horvat M. Effect of Taekwondo Training on Lower Body Strength and Balance in Young Adults with Down syndrome. J Policy Pract Intellect Disabil. 2016;13(2):165–172. doi: 10.1111/jppi.12164.
34. Gutiérrez-Vilahú L, Massó-Ortigosa N, Costa-Tutusaus L, Guerra-Balic M, Rey-Abella F. Effects of a Dance Program on Static Balance on a Platform in Young Adults With Down Syndrome. Adapt Phys Activ Q. 2016;33(3):233-252. doi: 10.1123/APAQ.2015-0048.
35. Moraru C, Hodorca RM, Vasilescu D. The Role of Gymnastics and Dance in Rehabilitating Motor Capacities in Children with Down syndrome. Sp Soc Int J Ph Ed. 2014;14:102-112.
36. Querido A, Marques-Aleixo I, Figueiredo P, Seifert L, Chollet D, Vilas-Boas JP, et al. Front crawl and backstroke arm coordination in swimmers with Down syndrome. In: Kjendlie P-L, Stallman RK, Cabri J, editors. Book of Proceedings of the XI Symposium on Biomechanics and Medicine in Swimming; 2010 Jun 16-19; Oslo, Norway: Norwegian School of Sport Science; 2010. p. 157-159.
37. Querido A, Marques-Aleixo I, Figueiredo P, Soares-Miranda L, Vilas-Boas JP, Corredeira R, et al. Coordinative characterization of front crawl swimmers with Down syndrome. Arch Exerc Health Dis. 2010;1(2):58-62.
38. Marques-Aleixo I, Querido A, Figueiredo P, Vilas-Boas JP, Corredeira R, Daly D, et al. Intracyclic Velocity Variation and Arm Coordination Assessment in Swimmers with Down Syndrome. Adapt Phys Activ Q. 2013;30(1):70-84.
39. Ulate FV, Campos AM. Effects of Weight Resistance Training on Swimmers with Down Syndrome. Retos: Nuevas Tendencias en Educación Física, Deportes y Recreación. 2011;1(19):10-14.
40. Querido A, Corredeira R, Vilas-Boas JP, Daly D, Fernandes RJ. Can swimmers with Down syndrome follow a visual pacer in an incremental protocol? In: Australian Institute of Sports, editors. Proceedings of the XII International Symposium on Biomechanics and Medicine in Swimming, 2014 April 28-May 2; Canberra, Australia: Australian Institute of Sports (AIS); 2014. p. 325-328.
41. Ayán-Perez C, Martínez-Lemos I, Lago-Ballesteros J, Carral JMC, Loira-Caminã N. Reliability and Validity of Physical Fitness Field-Based Tests in Down syndrome: A Systematic Review. J Policy Pract Intellect Disabil. 2016;13(2):142-156. doi: 10.1111/jppi.12155.
42. Boer PH, Moss SJ. Test–retest reliability and minimal detectable change scores of twelve functional fitness tests in adults with Down syndrome. Res Dev Disabil. 2016;48:176-185. doi: 10.1016/j.ridd.2015.10.022.
43. Ayán-Perez C, Martínez-Lemos RI, Cancela-Carral JM. Reliability and convergent validity of the 6-min run test in young adults with Down syndrome. Disabil Health J. 2017;10(1):105-113. doi: 10.1016/j.dhjo.2016.07.004.
44. Boer PH, Moss SJ. Validity of the 16-metre PACER and six-minute walk test

in adults with Down syndrome. Disabil Rehabil. 2016;38(26):2575-2583. doi: 10.3109/09638288.2015.1137982.
45. Aranha VP, Samuel AJ, Saxena S. Reliability and sensitivity to change of the timed standing balance test in children with Down syndrome. J Neurosci Rural Pract. 2016;7(1):77-82. doi: 10.4103/0976-3147.165412.
46. Bandong ANJ, Madriaga GO, Gorgon EJR. Reliability and validity of the Four Square Step Test in children with cerebral palsy and Down syndrome. Res Dev Disabil. 2015;47:39-47. doi: 10.1016/j.ridd.2015.08.012.
47. Bandini LG, Fleming RK, Scampini R, Gleason J, Must A. Is body mass index a useful measure of excess body fatness in adolescents and young adults with Down syndrome? J Intellect Disabil Res. 2013;57(11):1050-1057. doi: 10.1111/j.1365-2788.2012.01605.x.
48. Samur-San-Martin JE, Goncalves EM, Bertapelli F, Mendes RT, Guerra-Junior G. BMI cutoff point estimation as obesity diagnostic criteria in Down syndrome adolescents. Nutr Hosp. 2016;33(5):1090-1094. doi: 10.20960/nh.57.
49. Nascimento EF, Souza MK, Rosa TS, Melo GLR, Soares BRA, Sousa FEV, et al. Predictive Equation for Fat Percentage Based on Body Mass Index for Adolescents with Down Syndrome. JEPonline. 2016;19(4):77-84.
50. Freire F, Costa LT, Gorla JI. Indicators of obesity in young people with Down syndrome. Motricidade. 2014;10(2): 2-10. doi: 10.6063/motricidade.10(2).1196.
51. Esco MR, Nickerson BS, Bicard SC, Russell AR, Bishop PA. Agreement of BMI-Based Equations and DXA in Determining Body-Fat Percentage in Adults with Down syndrome. Adapt Phys Activ Q. 2016;33(1):89-96. doi: 10.1123/APAQ.2014-0240.
52. Nickerson BS, Esco MR, Bicard SC, Russell AR, Williford HN, Shaefer G. Validity of the body adiposity index in adults with Down syndrome. Res Dev Disabil. 2015;38:92-96. doi: 10.1016/j.ridd.2014.12.010.
53. Loveday SJ, Thompson JMD, Mitchell EA. Bioelectrical impedance for measuring percentage body fat in young persons with Down syndrome: validation with dual-energy absorptiometry. Acta Paediatr. 2012;101(5):491-495. doi:10.1111/j.1651-2227.2012.02821.x.
54. González-Agüero A, Matute-Llorente A, Gómez-Cabello A, Vicente-Rodríguez G, Casajús JA. Percentage of body fat in adolescents with Down syndrome: Estimation from skinfolds. Disabil Health J. 2017;10(1):100-104. doi: 10.1016/j.dhjo.2016.05.013.
55. Usera PC, Foley JT, Yun J. Cross-Validation of Field-Based Assessments of Body Composition for Individuals with Down syndrome. Adapt Phys Activ Q. 2005;22(2):198-206.
56. Boer PH. Accuracy of the prediction equation for the determination of maximum heart rate in adults with Down syndrome. J Intellect Disabil Res. 2017;61(1): 83-88. doi: 10.1111/jir.12345.
57. Chen C-C, Ringenbach SDR, Snow MS, Hunt LM. Validity of a pictorial Rate of Perceived Exertion Scale for monitoring exercise intensity in young adults with Down syndrome. Int J Dev Disabil. 2013;59(1):1-10. doi: 10.1179/2047387712Y.0000000005.
58. Agiovlasitis S, Motl RW, Ranadive SM, Fahs CA, Yan H, Echols GH, et al. Pre-

diction of oxygen uptake during over-ground walking in people with and without Down syndrome. Eur J Appl Physiol. 2011;111(8):1739-1745. doi: 10.1007/s00421-010-1812-0.
59. Seron BB, Greguol M. Assessment protocols of maximum oxygen consumption in young people with Down syndrome – A review. Res Dev Disabil. 2014; 35(3): 676–685. doi: 10.1016/j.ridd.2013.12.008.
60. Agiovlasitis S, Beets MW, Lamberth J, Pitetti, KH, Fernhall B. Accuracy of a piezoelectric pedometer in persons with and without Down syndrome. Res Dev Disabil. 2016;59:73-79. doi: 10.1016/j.ridd.2016.08.003.
61. Peiris CL, Cumming TB, Kramer S, Johnson L, Taylor NF, Shields N. Accelerometer use in young people with Down syndrome: A preliminary cross-validation and reliability study. J Intellect Dev Disabil. 2016;1-12. doi: 10.3109/13668250.2016.1260100.
62. Special Olympcis [Internet]. The Special Olympics – What we do. [cited 2017 May 5]. Available from: http://www.specialolympics.org/Sections/What_We_Do/What_We_Do.
63. Dykens EM, Cohen DJ. Effects of Special Olympics International on social acceptance in persons with mental retardation. J Am Acad Child Adolesc Psychiatry. 1996;35(2):223-229.
64. INAS: The International Federation for Intellectual Impairment Sport [Internet]. Promoting sport worldwide for athletes with an intellectual disability, autism and Down's Syndrome. [cited 2017 July 1]. Available from: http://www.inas.org/.
65. IPC: Paralympic Movement [Internet]. Official website of the Paralympic Movement. [cited 2017 July 1]. Available from: https://www.paralympic.org/.
66. Smedley G. Making a splash. Learn Disabil Pract. 2007;10(2):24-25.
67. SU-DS: Sports Union for athletes with Down syndrome [Internet]. About Us – Mission statement. [cited 2017 July 1]. Available from: http://www.su-ds.org/about-us/.

Aerobic Interval Versus Continuous Training at Low Volume and Vigorous Intensity

Laura Castro De Garay[1], Tony Meireles Dos Santos[2], Matthew Rhea[3], Victor Machado Reis[1]

Introduction

Different aerobic exercises such as walking (1), cycling (2) and running (3) are often used in physical exercise programs for improving physical health and performance. Running on the treadmill is an aerobic exercise activity commonly performed by active individuals in fitness centres with participants often following two primary styles: (a) continuous, uninterrupted exercise characterized by low-moderate intensity and long period (4) and (b) interval, with exercise efforts of moderate-high intensity, interspersed with periods of active or passive recovery (5, 6).

The physiological adaptations induced by the aerobic training depend mainly on the relative intensity of the exercise, stressing that vigorous aerobic exercise have positive effects greater than moderate, especially in improving aerobic power (7) and neuromuscular capacity (8). But, moderate aerobic training results in an improvement in health status (9), adherence (10) and weight loss (11). Often individuals attempt to perform higher volumes of training than necessary, resulting in a training intensity below optimal (12). Thus, the exercise intensity pre-determination is warranted for training prescription, especially when individualized fitness information is available (13).Although well documented in the literature that intense exercise have better performance benefits when compared to moderate intensity (14), either for untrained (9) or trained individuals (15), there are few contributions (15, 16) that address the effectiveness of a training program with an interval (IT) and continuous (CT) mode of training at the same total distance, frequency and average intensity for a period that is sufficient to enable adaptations.

A previous study that compared the effect of IT (with active and passive recovery) and CT, with the same training volume, found greater ef-

1. Research Center in Sports Sciences, Health Sciences & Human Development (CIDESD); University of Trás-os-Montes and Alto Douro; Vila Real, Portugal
2. Department of Physical Education; Federal University of Pernambuco; Recife, PE – Brazil
3. Human Movement Program; AT Still University; Mesa, Arizona, USA

fects in IT with a total volume less than 30-min (17). According to the authors, the duration of training depends on the aerobic fitness level and the individual's ability to perform high intensity efforts, followed by a specific recovery. Another study of ten weeks with cardiac patients on the treadmill, observed an increase in the total work performed when IT was performed at high intensities (80 - 90% VO2peak) compared to CT at moderate intensity (50 - 60% VO2peak) (18). Also, Nybo et al. (3) compared the effect of a vigorous IT with traditional intervention programs (CT and strength training) in untrained young individuals. Twelve weeks of training showed significant increases for IT on VO2max (14 ± 2%) when compared with the other two modes of intervention. Helgerud et al. (14) examined eight weeks (3 d · wk-1) of aerobic training and found improvements in VO2max in two IT groups (long interval, 4-min exercise interspersed with 4-min rest vs. short-interval, 15 s exercise interspersed with 15 s rest, both performed at 90 - 95%HRmax) when compared with two continuous groups (45-min at 70% HRmax; ~24-min at 85% HRmax).

Thus, the aim of this study was to compare physiologic adaptations to continuous and interval running at low volumes (4.2 km) and vigorous intensities performed over 14 weeks. We hypothesized that 14 weeks of interval training at the same volume as continuous training would result in greater improvements in physiological indicators of aerobic fitness.

Material and methods

Participants

Initially 35 subjects were recruited for participation in the study. Participants were randomly assigned to either an interval training (IT; n = 13) or continuous training (CT; n = 13). The subjects from control group (CG; n = 9) were selected between those who reported unavailability to complete all 46 training sessions and they did their normal daily physical activities. Two individuals during maximal exercise test (VO2) showed clinical impairment with test being interrupted by the doctor and a third individual, presented a plantar fasciitis in the early familiarization. They were all removed from the study. The values of pre-training maximal test showed no differences in maximal VO2 between the three groups. Thus, thirty-two adult males participated in the study. All subjects were healthy with no known musculoskeletal or cardiorespiratory disease and exercised regularly, with at least one year in aerobic activities (moderate to vigorous intensities), but not currently involved in a training program. They were instructed to continue normal daily activities and to refrain from beginning any other exercise training program until the completion of the study. Subjects were instructed to refrain from caffeine, heavy meals or heavy exercises 24 h before each testing session. Before and after the 14-wk intervention period, the subjects completed a total of four visits in the following order: pre-testing procedures (1) answer the questionnaires and explanations to the procedures, (2) anthropometrics measures, (3) maximal test; post-testing procedures (4) maximal test. All tests and training program were performed at the same time of the day in a controlled laboratory condition (temperature = 19-22 o C; relative humidity = 50-60%).

All subjects completed a Physical Activity Readiness Questionnaire, and signed an informed consent before participation, which thoroughly explained the training and testing procedures. The study was performed according to the Declaration of Helsinki, and the protocol was approved by Ministry of Health – The Human Ethics Committee of Clementino Fraga Filho Hospital of Rio de Janeiro Federal University, Rio de Janeiro, Brazil (no 58659/02471312.8.0000.5257). Participants characteristics are shown in Table 1.

	IT (N = 13)	CT (N = 11)	CG (N = 8)
Age	30.2 ± 0.8	30.5 ± 1.0	29.1 ± 4.4
Height	174 ± 0.1	175 ± 0.1	175 ± 0.1
BM	77.6 ± 13.5	76.6 ± 3.7	76.4 ± 10.9
FM	14.3 ± 6.0	11.9 ± 3.9	12.5 ± 4.9
BMI	25.6 ± 3.64	25.14 ± 1.4	24.8 ± 2.2

Tabel 1. Body mass, fat mass and body mass index for the two training groups and control.

Data are presented as mean ± SD for the three groups. IT, interval training; CT, continuous training; CG, control group. Age (years); Height (cm); BM, body mass (kg); FM, fat mass (%); BMI, body mass index (kg · m-2).

Anthropometry

The subjects underwent a set of anthropometric assessments, which followed the norms of the International Society for Advancement of Kinanthropometry – ISAKA (Stewart, Marfell-Jones, Olds, & de Ridder, 2011). Anthropometric measurements (body mass; fat mass and BMI) were collected. The seven skinfolds measurement were introduced in the equation proposed by Jackson and Pollock (1978) and the densities obtained by the equations were converted in body fat using the formula proposed by Siri (1961). Skinfold thickness was obtained by Sanny® professional skinfold calliper. The Body Mass Index (BMI) was calculated as the ratio between the weight and the square of the height (BMI = kg·m-2), in accordance with the recommendations of the World Health Organization - WHO (2008). To measure weight and height, a scale with a stadiometer were used (Filizola, S. Paulo, Brazil).

Maximal VO2 test

Electrodes (Micromed) were placed at the manubrium, right and left iliac crest for measured heart rate (HR) at derivation CM5, with the individual on the treadmill (Inbrasport Master Super ATL, Porto Alegre, Brazil) HR values were visualized through Elite software (Micromed Biotechnology, Brasília, Brazil). The individual was connected to a metabolic cart (VO2000, Aerosport, Medgraphics, St. Paul, Minnesota) and gas samples were collected and measured every 10 second during the test. The participants were submitted to a ramp protocol with an initial velocity of 8.0 km×h-1 (0% of inclination), with a 0.02% inclination increase every 10 s until a maximum of 18 km×h-1 (with 2% inclination). The test was terminated when voluntary exhaustion occurred. VO2 max was the highest VO2 value averaged for a 30-s period. Time to attain VO2max (tVO2max) was also measured. VO2max was the highest value averaged during a 30-s period. Maximal HR (HRmax) was the highest value averaged during a 30-s period.

Blood lactate concentration ([La])

Capillary blood samples (25 µl) were obtained from the finger of each subject during all tests and the [La] were measured using an (Accutrend®Plus Roche Diagnostics GmbH, Mannheim, Germany). The measuring range was 0.8–22 mmol·L-1 and the sample is collected (Accu-Chek® Softclix) and first applied to a coded yellow test strip (Accutrend BM-Roche). Blood was added to the strip by letting it drip from a finger; in accordance with the instrument's instructions. We never let the finger touch the strip's pad to exclude any possible interference due to the sweat. The [La] were collected pre-post training: on rest (sitting for five minutes), and 1st, 3rd and 5th-min immediately after the end of the test (on sitting position).

Heart Rate (HR) and Rating of Perceived Exertion (RPE)

Subjects were fitted with a chest strap monitor (RS800CX Polar, Kempele, Finland) for HR measurement. The HR was collected pre-and post-training: on rest (5-min sitting; before starting the test); 60-s to 120-s immediately after the end of the test (on sitting position). The assessment of RPE was made by Category Ratio Scale (CR10) used the Borg's table translated into Portuguese language which consists of a vertical scale from 0 to 10, where "0" represents no effort and "10" maximal effort. The subject rated the effort every minute of exercise. All subjects performed a familiarization session to this scale.

Training intervention

The current study was designed to compare the physiological effects between the two training regimes (IT and CT) and the control group. The subjects from IT and CT performed aerobic training running programs that consisted of three sessions per week, 20-min per session during a period of 14 weeks. A fourth day was used for missed session during the same week and to avoid anyone to be excluded by not completing a minimum of 42 (>90%) of the total 46 training sessions. Training was controlled and supervised for each subject by a physical education professional trained to control the running intensities and session time. ACSM (19) states that vigorous (77 - 95%HRmax) and near-maximal to maximal (≥ 96%HRmax) intensities can be used for developing and maintaining aerobic fitness. In the present study, the training intensities for both groups were adapted from the ACSM recommendations (19). Thus, we established the following criteria to intensities stimulus categories for IT: 79 - 87%HRmax (vigorous); 88 - 93%HRmax (Vigorous-near maximal); 94 - 99%HRmax (near maximal to maximal). The objective of the three zones of HR was to give to our interval running program a variety-load with no rest between the stimuli and a progression of load during 14-wk (Table 2). To CT we used a ~ 87%HRmax as optimal load for sustained in a constant-effort during 20-min, as calculated during equated total amount of work. During every session, HR was controlled with a Polar monitor, to ensure that the subject would exercise within the pre-defined HR zone. When a subject was behind the necessary intensity treadmill velocity was increased by 0.5 km×h-1 and when the subject was above it was decreased 0.5 km×h-1. Table 2 displays the training load in the two experimental groups during the 14-week period.

	Interval training (N = 13)			Continuous training (N = 11)
	Vigorous	Vigorous-near maximal	Near maximal to maximal	Vigorous
	79 - 87%HR_{max}	88 - 93%HR_{max}	94 - 99%HR_{max}	~ 87%HR_{max}
	(138 ± 9 - 164 ± 10 b·min^{-1})	(165 ± 10 - 172 ± 10 b·min^{-1})	(174 ± 10 - 183 ± 11 b·min^{-1})	(164 ± 7 b·min^{-1})
	duration (min)	duration (min)	duration (min)	duration (min)
Week 1 - 2	44-min	110-min	36-min	200-min
	18 x 1 min 13 x 2 min	27 x 1 min 9 x 3 min 13 x 2 min 5 x 4 min 2 x 5 min	36 x 1 min	10 x 20 min
Week 3 - 4	28-min	46-min	40-min	120-min
	7 x 1 min 7 x 2 min 1 x 3 min 1 x 4 min	29 x 1 min 2 x 2 min 3 x 3 min 1 x 4 min	20 x 1 min 3 x 2 min 6 x 3 min	6 x 20 min
	37-min	36-min	41-min	120-min
	23 x 1 min 2 x 3 min	33 x 1 min 1 x 3 min	19 x 1 min 5 x 2 min 4 x 3 min	6 x 20 min
Week 5 - 6	25-min	33-min	56-min	120-min
	7 x 1 min 5 x 2 min 1 x 3 min 1 x 5 min	5 x 1 min 10 x 2 min 2 x 4 min	3 x 2 min 6 x 3 min 8 x 4 min	6 x 20 min
	24-min	63-min	27-min	120-min
	10 x 1 min 7 x 2 min	22 x 1 min 9 x 2 min 5 x 3 min 2 x 4 min	27 x 1 min	6 x 20 min
Week 7 - 8	26-min	65-min	23-min	120-min
	10 x 1 min 8 x 2 min	19 x 1 min 8 x 2 min 4 x 3 min 3 x 4 min 1 x 6 min	23 x 1 min	6 x 20 min

Week 9 - 10	26-min	48-min	40-min	120-min
	14 x 1 min 6 x 2 min	20 x 1 min 4 x 2 min 4 x 3 min 2 x 4 min	12 x 1 min 4 x 2 min 4 x 3 min 2 x 4 min	6 x 20 min
Week 11 - 12	44-min	110-min	36-min	200-min
	18 x 1 min 13 x 2 min	27 x 1 min 9 x 3 min 13 x 2 min 5 x 4 min 2 x 5 min	36 x 1 min	10 x 20 min
Week 13 - 14	28-min	46-min	40-min	120-min
	7 x 1 min 7 x 2 min 1 x 3 min 1 x 4 min	29 x 1 min 2 x 2 min 3 x 3 min 1 x 4 min	20 x 1 min 3 x 2 min 6 x 3 min	6 x 20 min
	37-min	36-min	41-min	120-min
	23 x 1 min 2 x 3 min	33 x 1 min 1 x 3 min	19 x 1 min 5 x 2 min 4 x 3 min	6 x 20 min

Week 1 -2 was used to equate training load (20-min/session, 5 d · wk-1); week 3 to 14 (20-min/session, 3 d · wk-1). All sessions for both groups (IT and CT) started with 1-min warm-up at moderate intensity (64-76%HRmax)

Tabel 2. Distribution of work for interval training (IT) and continuous training (CT) for 14 weeks.

Statistical analysis

Data were expressed as mean and standard deviation. Heart Rate and Blood Lactate were compared by analysis of variance (ANOVA) with 2 factors (Group x Time) with repeated measures for Time. Absolute and relative VO2, tVO2, Fat Mass, Body Mass and RPE were compared with repeated measures ANOVA. Whenever ANOVA was significant, the Tukey-Kramer post hoc was used. The criterion for significant differences was set at p £ 0.05 All analyses were performed using the R software version 15.0 (R Foundation for Statistical Computing, Austria, 2012).

Results

All measurements before and after the 14-wk of running training for the three groups can be seen at Table 3 There was interaction between Group x Time. There were no differences observed at baseline between any of the 3 groups for age, height, mass, BMI. Further, there were no changes for any anthropometric variable after 14-wk of training. Of the 24 participants who completed the training program (IT and CT) all attended at least 90% of the training sessions. There was no difference in adherence across groups.

	IT	(N = 13)	CT	(N = 11)	CG	(N = 8)
	Pre	Post	Pre	Post	Pre	Post
VO_2 mL×kg^{1}×min^{1}	47.8 ± 6.3	51.7±5.9*	50.9 ± 6.0	52.8 ± 5.1	49.7 ± 5.6	49.4± 6.4
L.min	3.67 ± 0.6	4.0±0.6*	3.89 ± 0.3	4.0 ± 0.3	3.8 ± 0.5	3.7 ± 0.4
tVO_{2max} min	9.2 ± 0.8	10.2±0.7*	10.5 ± 1.1	10.7 ± 1.0	9.6 ± 1.8	9.5 ± 1.9
HR b·min^{-1}						
rest	69 ± 10	59 ± 9*	67 ± 10	57 ± 2*	66 ± 8	64 ± 10
max	185 ± 11	187 ± 11	183 ± 9	185 ± 10	190 ± 6	191 ± 8
60s	122 ± 20	121 ± 10	116 ± 10	117 ± 13	123 ± 23	123 ± 15
120s	110±14**	109±11**	107±9**	108±14**	112±18**	112±14**
[La] mmol·L^{-1}						
rest	2.55± 0.38	2.73± 0.39	2.40± 0.20	2.29± 0.45	2.36± 0.23	2.68± 0.23
1-min	12.03± 2.89	13.14±2.57†	12.21±2.49	13.23±1.57†	13.41 1.54	13.30±1.39
3-min	11.42± 2.23	12.66±2.50†	11.97±2.9	12.88±1.65†	12.88±1.56	13.44±1.56†
5-min	9.74±3.4***	13.00± 2.58†	11.5±2.74	12.9±1.49†	12.26±1.74	13.45±1.40†
RPE	9 ± 1	9 ± 1	9 ± 1	9 ± 1	9 ± 1	9 ± 1

Table 3. Changes in physiological parameters pre- to post training.

Data are presented as mean ± SD. The maximal test was carried out running on a treadmill on ramp protocol for all groups, IT, interval training; CT, continuous training; CG, control group. VO2, oxygen uptake, relative and absolute VO2max (mL×kg-1×min1 and L×min-1); tVO2max, maximal time reached on maximal test until voluntary exhaustion; HR, heart rate on rest (5-min before test on sitting position), max, maximal heart rate on test, 60-s and 120-s after ending effort (on sitting position); [La], blood lactate concentration on rest (5-min before test on sitting position), 1-min, 3-min and 5-min after ending effort (on sitting position); RPE, rating of perceived exertion (maximal value). * higher compared with pre-training values; ** lower compared with 60-s in the same group and measure; *** lower compared with 3-min in the same group and measure. † higher compared with pre-training values in the same group and time; $p < 0.05$ in all the preview.

Relative and absolute VO2max (mL×kg-1×min1 and L×min-1) increased 2.47 and 3.96% only in interval training group, as seen in Table 3. The initial VO2max of all three groups was similar. Time of the maximal test performed pre- and post-training showed interaction between the groups. The IT after 14 weeks showed a significant increase (10%; p <0.001) when compared with CT and CG. resting heart rate showed a decrease for IT and CT after 14-wk of training, despite no significant interaction between groups. Post-training a lower mean HR was found in all groups, when compared with pre-, at 120-s of recovery compared with 60-s of recovery (Table 3). There were no differences in blood lactate between groups. There were no changes in resting [La] after 14-wk of training, but differences were found between pre-vs. post-training in recovery [La] measured at minutes one, three and five (Table 3).

Discussion

The major finding of the present study was that aerobic interval training with a low training duration (60 min×wk-1) at vigorous to maximal intensities not only resulted in improved on aerobic power (VO2peak) but also increased maximal time achieved on the VO2 test until voluntary exhaustion.

Blood lactate concentration

The present study found higher post-maximal test [La] in both experimental groups at various measurement times (1st,3rd,5th-min), after 14-wk of training. We cannot conclude that these values increased due to longer maximal effort, because only the IT group showed increases on tVO2max (11.08%) and less due to training mode because there was no interaction between training groups for this variable All groups increased metabolic glycolytic potential over 14 weeks of training. Mandroukas et al. (17) investigated physically active youth, for the same amount of running (32-min) in three different modes (active recovery IT; passive recovery IT and continuous training) and concluded that lactate is removed faster when recovery is active. For the authors, possible explanation is that blood lactate is used as energy substrate in aerobic energy production by inactive muscles and that the primary factor for the increase in [La] after exercise is the duration and intensity (high) effort in which the individual has undertaken. Others (20) pointed out that the high [La] measured immediately after exercise remain elevated between 3 to 8 min, and up to approximately the 60-min [La] be likely to decrease progressively. For our study, we hypothesized that training mode (continuous or interval) would not affect the [La] after maximal efforts. Both groups showed decrease of [La] between 1st and 5th-min. We conclude that a 3-min recovery was not enough to induce significant changes in [La]. In the present study, after maximal efforts, at least five minutes of passive recovery were required to level-off [La].

Heart Rate

Even though all subjects were fit before the experiment, decreases on resting heart rate (8.86%) were found, may be because of the exercise mode (running). The literature (21) suggests that this reduction is due to increased venous return. Typically, individuals with a low resting HR have increased parasympathetic activity and decreased sympathetic activity. In aerobically trained individuals this response is expected. The resting bradycardia is one of the adaptations after chronic exercise. There were no changes after 14-wk in HRmax, HR60s and HR120s (recovery). However, as expected, all groups showed HR decrease immediately after maximal effort from 60-s to 120-s. Some (22) described training adaptations in recovery HR, but in the present study these adaptations were only observed in resting HR, corroborating previous findings with running (3). In relation to rating of perceived exertion no change was observed despite the interval training group had increased the total time at maximal effort after 14-wk of training.

Maximal VO2

The most important finding of our results was that only individuals who performed interval training showed improved values of maximal VO2 after 46 sessions of running training. The value of VO2 max is an important predictor of performance and has been used in the prescription of exercise. The duration and intensity of the stimulus directly affects the magnitude of the adaptation to aerobic training and these benefits are verified mainly with interval work durations from three to five minutes (24). The adaptations observed in this study for interval training group were higher compared with that in the continuous training group and may be due to central and peripheral adaptations that may result in higher performance (14). Some stated that IT when performed at intensities below 80%VO2max offers no improvement over CT at the same intensity (23); while others (25) reported that the best gains comes from IT with a (2:2) exercise/recovery ratio. In agreement with our results, several (14, 18 ,28) have verified that IT at 80-90% provides significant improvements relative to the CT 50-75 VO2max in healthy subjects. Recently (29) such benefits were observed at 12-wk of IT with low volume and high intensity where a group ran (20-min; 2 d.wk-1) at 1 (89%VO2max): 1 (10%VO2max) and other a CT at high volume (30 - 50 min; 2 d.wk-1) and moderate intensity (58%VO2max).

Some authors have not found differences between training (IT and CT) for 10 weeks of exercise (26). The limited duration of the continuous running training herein can also help to explain the minor adaptations, as others (18) recorded improvements in VO2peak after a higher training volume than that herein (> 20-min). Training interval when performed in a maximum intensity or higher and relatively short recovery time (2:1) apparently shows improvements for the development of aerobic and anaerobic systems, but if the recovery time is very short, stagnation occurs in early exercise. Some authors (30) pointed out the need to equate the interval and continuous training by distance performed or other equivalent variable and that when the intensity is below 80%VO2max) exercise is maintained without major difficulties and can thus be performed in continuous mode. Although, as noted in the literature, it is necessary to point out that for high intensity exercise (90-120%VO2max) is necessary to prescribe training periods or intervals that enable a sufficient volume. Moreover, Gibala (31) recommends that when a minimum volume is performed a high stimuli intensity should be done to obtain gains. An important aspect is that our training at “low-volume” showed benefits without the need to stress individuals on popular high-intensity training as HIT.

Total time on maximal test (tVO2max)

IT showed a 11.08% increased (9.2 ± 0.8 min vs. 10.2 ± 0.7 min) 14-wk of running. Authors (32) described IT and TC improvements in exercise time (4.0%) in tVO2max after 7 weeks of training. Although the authors have conducted stimuli shorter than that in the present study, the reduction in training volume (~ 50%) showed benefits on active subjects. Others (37) reported that combining low volume of aerobic sessions in continuous mode (75-85%HRmax) with high-intensity interval training and sprint training improved by 1-min the time to run 10km, after 6 weeks of training. Moore et al. (32) found during a 10-wk of running training, improvement in the maximum time until volitional exhaustion (16.4 ± 3.2

vs. 17.3 ± 2.8 min, $p<0.05$), despite not having improvements for maximal VO2. For the author (31) improvement in performance (time) was due to peripheral adaptations. In our study, we did not find performance improvements in the training group that exercised at constant loads (CT).

Conclusions

Interval training in the current study presented a significant improvement in maximal oxygen uptake and in time on maximal effort. However, 14-wk of continuous running had no impact on aerobic fitness indicators that were assessed. Hence, we can conclude that interval training at a minimum of 20-min performed three times per week is sufficient for fitness improvement and more appropriate when compared with continuous training of similar volume.

References

1. Chomistek AK, Cook NR, Flint AJ, Rimm EB. Vigorous-intensity leisure-time physical activity and risk of major chronic disease in men. Med Sci Sports Exerc. 2012 Oct;44(10):1898.
2. Støren Ø, Bratland-Sanda S, Haave M, Helgerud J. Improved V [Combining Dot Above] O2max and Time Trial Performance With More High Aerobic Intensity Interval Training and Reduced Training Volume: A Case Study on an Elite National Cyclist. J Strength Cond Res. 2012 Oct 1;26(10):2705-11.
3. Nybo L, Sundstrup E, Jakobsen MD, Mohr M, Hornstrup T, Simonsen L, Bülow J, Randers MB, Nielsen JJ, Aagaard P, Krustrup P. High-intensity training versus traditional exercise interventions for promoting health. Med Sci Sports Exerc. 2010 Oct 1;42(10):1951-8.
4. Kraus WE, Houmard JA, Duscha BD, Knetzger KJ, Wharton MB, McCartney JS, Bales CW, Henes S, Samsa GP, Otvos JD, Kulkarni KR. Effects of the amount and intensity of exercise on plasma lipoproteins. N Engl J Med. 2002 Nov 7;347(19):1483-92.
5. Dupont G, Berthoin S. Time Spent at a High Percentage of max for Short Intermittent Runs: Active Versus Passive Recovery. Can J Sport Sci. 2004 Oct;29(S1):S3-16.
6. Glaister M, Stone MH, Stewart AM, Hughes MG, Moir GL. Aerobic and anaerobic correlates of multiple sprint cycling performance. J Strength Cond Res. 2006 Nov 1;20(4):792-8.
7. Wakefield BR, Glaister M. Influence of work-interval intensity and duration on time spent at a high percentage of VO2max during intermittent supramaximal exercise. J Strength Cond Res. 2009 Dec 1;23(9):2548-54.
8. McKay BR, Paterson DH, Kowalchuk JM. Effect of short-term high-intensity interval training vs. continuous training on O2 uptake kinetics, muscle deoxygenation, and exercise performance. J Appl Physiol. 2009 Jul 1;107(1):128-38.
9. Bradley PS, Mohr M, Bendiksen M, Randers MB, Flindt M, Barnes C, Hood P, Gomez A, Andersen JL, Di Mascio M, Bangsbo J. Sub-maximal and maxi-

mal Yo–Yo intermittent endurance test level 2: heart rate response, reproducibility and application to elite soccer. Eur J Appl Physiol. 2011 Jun 1;111(6):969-78.

10. Standage M, Sebire SJ, Loney T. Does exercise motivation predict engagement in objectively assessed bouts of moderate-intensity exercise? A self-determination theory perspective. J Sport Exercise Psy. 2008 Aug;30(4):337-52.
11. Boutcher SH. High-intensity intermittent exercise and fat loss. J Obes. 2010 Nov 24;2011.
12. Berg K. Endurance training and performance in runners. Sports Med. 2003 Jan 1;33(1):59-73.
13. American College of Sports Medicine. ACSM's guidelines for exercise testing and prescription. Lippincott Williams & Wilkins; 2013 Mar 4.
14. Helgerud J, Hoydal K, Wang E, Karlsen T, Berg P, Bjerkaas M, Simonsen T, Helgesen C, Hjorth N, Bach R, Hoff J. Aerobic High-Intensity Intervals Improve VO2max More Than Moderate Training. Med Sci Sports Exerc. 2007 Apr 1;39(4):665.
15. Swain DP. Moderate or vigorous intensity exercise: which is better for improving aerobic fitness? Prev Cardiol. 2005 Jan 1;8(1):55-8.
16. Glaister M. Multiple sprint work. Sports Med. 2005 Sep 1;35(9):757-77.
17. Mandroukas A, Heller J, Metaxas TI, Sendelides T, Riganas C, Vamvakoudis E, Christoulas K, Stefanidis P, Karagiannis V, Kyparos A, Mandroukas K. Cardiorespiratory and metabolic alterations during exercise and passive recovery after three modes of exercise. J Strength Cond Res. 2011 Jun 1;25(6):1664-72.
18. Rognmo Ø, Hetland E, Helgerud J, Hoff J, Slørdahl SA. High intensity aerobic interval exercise is superior to moderate intensity exercise for increasing aerobic capacity in patients with coronary artery disease. Eur J Cardiol Prev Rehab. 2004 Jun 1;11(3):216-22.
19. Garber CE, Blissmer B, Deschenes MR, Franklin BA, Lamonte MJ, Lee IM, Nieman DC, Swain DP. American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. Med Sci Sports Exerc. 2011 Jul;43(7):1334-59.
20. Goodwin ML, Harris JE, Hernández A, Gladden LB. Blood lactate measurements and analysis during exercise: a guide for clinicians. J Diabetes Sci Tech. 2007 Jul;1(4):558-69.
21. Moholdt T, Aamot IL, Granøien I, Gjerde L, Myklebust G, Walderhaug L, Brattbakk L, Hole T, Graven T, Stølen TO, Amundsen BH. Aerobic interval training increases peak oxygen uptake more than usual care exercise training in myocardial infarction patients: a randomized controlled study. Clin Reab. 2012 Jan;26(1):33-44.
22. Thompson PD, Crouse SF, Goodpaster BR, Kelley D, Moyna NI, Pescatello LI. The acute versus the chronic response to exercise. Med Sci Sports Exerc. 2001 Jun;33(6 Suppl): S438-45.
23. Overend TJ, Paterson DH, Cunningham DA. The effect of interval and continuous training on the aerobic parameters. Can J Sport Sci. 1992 Jun

1;17(2):129-34.
24. MacDougall D, Sale D. Continuous vs. interval training: a review for the athlete and the coach. Canadian journal of applied sport sciences. J Can Sci App Sport. 1981 Jun;6(2):93-7.
25. Gibala MJ, Little JP, MacDonald MJ, Hawley JA. Physiological adaptations to low volume, high intensity interval training in health and disease. J Psychol. 2012 Mar 1;590(5):1077-84.
26. Swain DP, Franklin BA. Comparison of cardioprotective benefits of vigorous versus moderate intensity aerobic exercise. Am J Cardiol. 2006 Jan 1;97(1):141-7.
27. Thomas TR, Adeniran SB, Etheridge GL. Effects of different running programs on VO2 max, percent fat, and plasma lipids. Canadian journal of applied sport sciences. J Can Sci App Sport. 1984 Jun;9(2):55-62.
28. Currie KD, Dubberley JB, McKELVIE RS, MacDonald MJ. Low-volume, high-intensity interval training in patients with CAD. Med Sci Sports Exerc. 2013 Aug 1;45(8):1436-42.
29. Tuimil JL, Boullosa DA, Fernández-del-Olmo MÁ, Rodríguez FA. Effect of equated continuous and interval running programs on endurance performance and jump capacity. J Strength Cond Res. 2011 Aug 1;25(8):2205-11.
30. Gibala MJ. High-intensity interval training: a time-efficient strategy for health promotion? Curr Sport Med Rep. 2007 Jul;6(4):211-3.
31. Gunnarsson TP, Bangsbo J. The 10-20-30 training concept improves performance and health profile in moderately trained runners. J Appl Physiol. 2012 Jul 1;113(1):16-24.
32. Moore IS, Jones AM, Dixon SJ. Mechanisms for improved running economy in beginner runners. Med Sci Sports Exerc. 2012 Sep 1;44(9):1756-63.

Comparison of energy expenditure during self-selected walking in field tracks and in treadmill at various grades

João Paulo Brito[1], Ana Conceição[1,2], Félix Romero[1], Adenilson Targino de Araújo Junior[3], Victor Machado Reis[2,3]

Introduction

Despite the growing popularity of performing regular walks and the medical recommendations for their achievement, little is known about the level of effort induced by the practice of field tracks walks (1). Most previous studies (2, 3) examined the practice of walking in laboratory conditions. Energy Expenditure (E) has a critical role in locomotion (4), as body adjusts/controls the E according to the energy needed for the task (5).

Using data from the kinematics, Hoffman and colleagues (2) confirmed that the conditions of instability of field tracks increase the E when compared with walks under controlled conditions. Larger steps caused by rough ground may involve a higher E because of the cost of transition between feet (6). However, for Menz and colleagues (7) walking in areas with small obstacles (up to 25 mm) does not seem to be a significant factor in changing patterns of motion. In a comparative study, Hall and colleagues (8) say that even when walking on land is held on flat surfaces, we need more energy for the field tracks than in the motorized treadmill. According to these authors, it is not possible to estimate the E of field tracks motion based on laboratory values.

Pearce and colleagues (9) stated that the E of motion in a rigid surface is higher than that in a motorized treadmill for a pre-determined speed. On the other hand, walking on a slope can change significantly the E (10, 11). Thus, when prescribing field tracks walks as a physical exercise it is necessary to know the E involved while walking on sloping terrain and its reliability in a motorized treadmill. The physiological responses are

---

1. Sports Sciences Research Laboratory, Sports Sciences School of Rio Maior, Polytechnic Institute of Santarém, Portugal
2. Research Center in Sport Sciences, Health Sciences & Human Development (CIDESD), Portugal
3. Department of Sport Sciences, Exercise & Health, University of Trás-os-Montes and Alto Douro, Portugal

sensitive to the increase in slope (10) and increasing the difficulty of the terrain may cause a significant increase in E (12).

When walking in field tracks, it may occur various changes in the relative contribution of the E and in the optimization of the motion stability (13). If the E constraint contribution was critical, it would be expectable to present adaptation responses to reduce energy costs. Nevertheless, the adaptation processes during locomotion tend to optimize the relation between efficiency of movement and E (14). The use of a self-selected speed seems to result, for most subjects, in E lower than when it is imposed (10).

DeVoe and colleagues (12) reported that despite the various constrains imposed by the ground irregularities, the self-selected speed is the most economical for most subjects allowing the execution of movement for long periods of time. When walking takes place in varies soils, there may be variations in the speed selected by the subjects to offset the soil difficulties (15). Recent research reports scarce conclusive results in what concerns field versus laboratory walking; Therefore, the present study aims to compare the energy expenditure. Oxygen consumption, heart rate and speed necessary to walk in field tracks and on motorized treadmill at different slopes.

Material and Methods

Participants

Twenty-one male subjects (age 23.43 ± 2.43 years; body weight 77.46 ± 13.43 kg, height 1.75 ± 0.08 m; fat mass estimated 15.09 ± 5.42%; consumption of oxygen at rest 3.17 ± 0.37 $ml.kg^{-1}.min^{-1}$), physically active (exercising at least for three times per week over the past 6-month period) and who had no history of orthopaedic injury, volunteered for this study. All procedures followed the Helsinki Declaration of 1975 and were approved by the ethics committee of the institution were the study took part.

Experimental protocol

On their first visit to the laboratory, subjects' body mass and height were measured with a scale and stadiometer (SECA, Germany, Hamburg) and fat mass was measured estimated using Bio Impedance Analysis method (Omron BF300, Matsusaka Co. LTD., Japan). The subjects did not exercise for 12-h prior to the exercise sessions and did not ingested caffeine within 3-h before exercise. These measurements were performed under a minimum 8-h fasting.

After this evaluation, the subjects had a light meal and 3-h later they started walking in field tracks. Wenty-four hours later the subjects completed three periods of walking in the countryside tracks with an interval of 30 min (a starting VO_2 with a difference less than 2.1 $ml.kg^{-1}.min^{-1}$ to that observed before the start of the first period of effort was required). The three segments of the course in field tracks had a mean slope and distance of 0%, 6% and 14% and 821, 618 and 598 metres, respectively. On each track, maximum slope variation was 1%.

We used forest segments of footpaths and roads with hard soil ground predominantly of gravel, without any obstacles. The route segments were evaluated via planimetric and altimetric survey (Sokkia 130R, Casagiove, Italy) and only the routes that respected a variability of slope equal to or inferior to 1% over the entire distance of the segment were selected. The tests took place during the morning with temperatures between 20 and 22°C and humidity between 50 and 60%.

Before and during the sessions in field tracks, the wind speed was measured with a portable anemometer instrument brand Xplorer, model SkywatchXplorer 3 (JDC Electronic, Yverddon-les-Bains, Switzerland). The tests took place whenever the wind speed was inferior to 15 $km.h^{-1}$, speed up to which the aerodynamic resistance is considered negligible, according to Di Prampero (16). When the wind speed exceeded 15 $km.h^{-1}$, the test was stopped and repeated 24-h later. The walking speed on the field tracks was self-selected as suggestion by literature (17, 18).

Prior to the test, subjects were asked to select a comfortable walking speed that would allow them to perform up to a 15-km track. Throughout the route, subjects were followed by an investigator riding a bicycle with a digital velocimeter (MSC-2DXC, AT EYE Co., LTD, Osaka, Japan) and were asked to return to the walking speed they self-selected during the first two minutes of the trial whenever they deviated more than 0.2 $km.h^{-1}$ from the self-selected speed. Forty-eight hours later, all field tests were repeated on a motorized treadmill RunRace (Tecnogym, Gambottela, Italy), calibrated according to the manufacturer´s guidelines. The subjects exercised in the treadmill with the same distance, slope and walking speeds that were performed during the three segments of the field tracks

During all exercise sessions, VO_2 was measured using direct oximetry with a gas analyser Cosmed $K4b_2$ (Cosmed, Rome, Italy) and heart rate (HR) was measured using a POLAR chest belt coupled to the $K4b^2$. The E was calculated by the software $K4b^2$ based on the quantities of the expired VCO_2 and VO_2 (19). Data were processed using the software

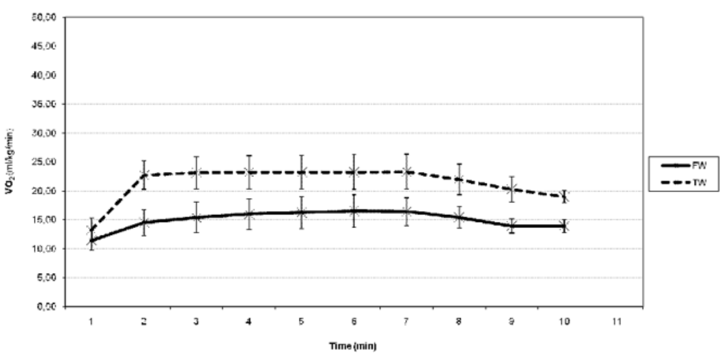
Cosmed PFT Suite version 7.4b (Cosmed, Rome, Italy). During each segment of the route, the values of the HR and VO_2 of the subjects were monitored by telemetry. The VO_2 values were recorded every 20-s (20) and then averaged per minute to subsequent calculations. To ensure the existence of a plateau in VO_2, the maximum difference allowed between three 20-s consecutive average VO_2 values was less than 2.1 $ml.kg^{-1}.min^{-1}$. Heart rate was measured concomitantly to VO_2, E was calculated by the manufacturer's software. Tests were carried out to the calibration of the analyser, indicated by the manufacturer, before each use: reference gas calibration with O_2 = 16% and CO_2 =5%, turbine calibration with a 3 litres syringe) delay calibration and room air calibration.

Statistics

The data were analysed using SPSS software version 17.0 (Science, Chicago, USA). A repeated measures ANOVA was used to confront the average values of the final min of each variable in the different conditions of exercise. To verify the 'sphericity', it was used the 'sphericity test of Mauchly." Whenever the assumption of "sphericity" was not the observed, we used the correction factor of Greenhouse-Epsilon Geisse, as it is the most conservative and appropriate for a small size sample (21). For all statistical procedures, the minimum level of significance admitted was $P \leq 0.05$.

Results

After analysing the curves of the minute values of VO_2, it was confirmed that the stabilization of VO_2 occurred, basic condition for the use of these numbers as an indicator of E. Figure 1 shows the typical behaviour of VO_2 in the six journeys made (values of a representative subject).



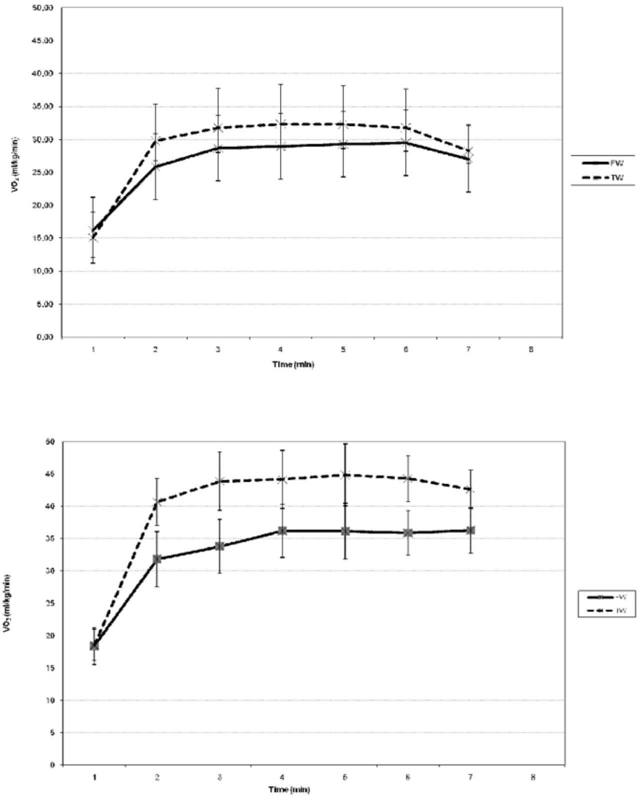


Figure 1. Means (full lines and dotted lines) and standard deviations (error bars) of VO_2 while walking in motorized treadmill (TW) and in nature (FW) with 0% gradient (upper panel), 6% gradient (middle panel) and 14% gradient (lower panel).

The values of the average per minutes of the VO_2, E and HR of walking on a motorized treadmill (TW) were higher than those of the walking in field track (FW) on all slopes. In all the average comparisons of the studied variables, there were no differences in the following comparisons: FW slope with 6% *vs* TW with slope of 6% to the variable FC; FW with slope of 0% *vs* FW with slope of 6%, for variable speed (see Table 1). A change of 6% in the slope did not cause differences in the walking speed. However, when the comparisons slope 0 *vs* 14% slope and slope 6 vs 14% slope were made, there is a lower rate of displacement, for a significance of, P ≤ 0.05 and 0.01, respectively.

Exercise condition		VO_2	HR	E	S		
		($ml.kg^{-1}.min^{-1}$)	($b.min^{-1}$)	($kcal.min^{-1}$)	($m.s^{-1}$)		
FW slope 0%	vs	TW slope 0%	dif.	6.44**	12.59**	2.29**	-
			IC 95%	4.88 to 8.01	3.44 a 21.75	1.56 to 3.01	-
FW slope 6%	vs	TW slope 6%	dif.	5.66**	3.17	1.10*	-
			IC 95%	1.56 to 9.75	-5.31 a 11.65	0.14 to 2.06	-
FW slope 14%	vs	TW slope 14%	dif.	12.25**	15.01**	2.95**	-
			IC 95%	9.28 to 15.23	6.43 a 23.6	1.92 to 3.99	-
FW slope 0%	vs	FW slope 6%	dif.	11.24**	25.58**	4.01**	0.05
			IC 95%	7.54 to 14.94	19.35 a 31.8	3.14 to 4.89	-0.02 to 0.12
FW slope 0%	vs	FW slope 14%	dif.	16.86**	37.89**	6.31**	0.15*
			IC 95%	14.16 to 19.57	31.05 a 44.73	5.39 to 7.23	0.05 to 0.24
FW Slope 6%	vs	FW slope 14%	dif.	5.63**	12.31**	2.30**	0.10**
			IC 95%	2.78 to 8.47	8 a 16.63	1.63 to 2.97	0.05 to 0.15
TW slope 0%	vs	TW slope 6%	dif.	10.45**	16.15**	2.83**	-
			IC 95%	8.07 to 12.82	10.35 a 21.95	2.03 to 3.62	-
TW slope 0%	vs	TW slope 14%	dif.	22.67**	40.31**	6.98**	-
			IC 95%	19.39 to 25.96	31.46 a 49.16	5.68 to 8.28	-
TW slope 6%	vs	TW slope 14%	dif.	12.22**	24.16**	4.15**	-
			IC 95%	10.06 to 14.38	20.33 a 27.98	3.43 to 4.88	-

VO_2 = oxygen uptake; HR = heart rate; E = energy expenditure; S = speed; *, **Statistically significant differences in average for *P*≤0.05 and 0.001, respectively.

Table 1. Average difference (dif.) and confidence interval (95% CI) of differences of the comparisons of different exercise conditions and slope - walking on a motorized treadmill (TW) vs in field tracks (FW) in the slopes 0% (n = 21), 6% (n = 21) and 14% (n = 19) for variable speed (S), oxygen consumption (VO_2), heart rate (HR) and the energy (E).

Discussion

Results show a progressive increase in VO_2, E and HR with slope, either in FW or in the TW conditions of exercise. The E and the VO_2 were higher in TW compared with FW condition. Average speed was also higher in TW (1.64 ± 0.16 ms^{-1} at slope 0%, 1.59 ± 0.14 ms^{-1}, at slope 6%; 1.49 ± 0.13 ms^{-1} and at slope 14%) when compared with self-selected speed. These corroborate the results of Bertram and Ruina (22), Falola and colleagues (23) and that by DeVoe and colleagues (12), which state that the self-selected speed by the subjects is not always the most economical. Although Bobbert (11) and Margaria (24) claim that the optimal walking speed in slopes above 10% is 1.0 ms^{-1}, in the present study, at slopes of 6% and 14%, we observed that the self-selected velocities were higher than those by Bobbert (11) and by Margaria (24).

The values of E, VO_2 and HR are lower in the field tracks walking for self-selected velocities and are similar to those of Church and colleagues (25), for the slope of 0% in land, 5.7 ± 1.3 $kcal.min^{-1}$, 12.8 ± 1.8 $ml.kg^{-1}.min^{-1}$ and 101.6 ± 12.0 $beat.min^{-1}$, respectively. These results differ from those found by Pearce and colleagues (9) where significant differences were confirmed in VO_2 of walking in a motorized treadmill *vs* on a hard surface (respectively, 10.58 and 11.04 $ml.kg^{-1}.min^{-1}$). However, these results were found with subjects aged from 55 to 66 years while we examined the response of young adult subjects (aged 23.6 ± 2.43). Despite not having measured the E, Murray and colleagues (26) found no differences between the cinematic walking in the motorized treadmill and in rigid surface, but the electromyography activity and HR were higher in the motorized treadmill.

Some (27, 28) have previously reported that there is an intra-subject variability in the E during the walking on the motorized treadmill. On the contrary, Bertram and Ruina (22) claim that walking on motorized treadmill mimics the natural constraints of the walking, presenting itself as an alternative of replication to the data extrapolating from the laboratory environment to the natural environment. There is no consensus that the oxygen consumption values are higher or lower in the motorized treadmill vs field tracks (26, 29, 30, 31).

The increase in the E, with the increment of the slope was previously described by Alexander (10). This study also found that the E increased progressively with the increases of the slope. This phenomenon was observed in both walking on a motorized treadmill and in field tracks. Nevertheless, in walking on a motorized treadmill there was a greater intersubject variability compared with walking in field tracks. Johnson and colleagues (32) found VO_2 values of 10.79, 15.05 and 20.59 $ml.kg^{-1}.min^{-1}$, in walking on motorized treadmill with constant speed of 1.11 ms^{-1}, at 0%, 5% and 15%, slope respectively. Our values for the progressive slopes were 21.91, 32.36 and 44.58 $ml.kg^{-1}.min^{-1}$, with self-selected velocities of 1.64 ± 0.16, 1.59 ± 0.14 and 1.49 ± 0.13 ms^{-1}, respectively at grade, 6% and 14%.

The higher walking velocities used by the subjects in the current study (1.64 ± 0.16, 1.59 ± 0.14 and 1.49 ± 0.13 ms^{-1}, respectively), compared with those in the study by Johnson and colleagues (32), may explain the higher mean values of VO_2. Our VO_2 mean values are also higher than those described by Gottschall and Kram (3), which report average values of 7.4 ± 0.7 $ml.kg^{-1}.min^{-1}$ walking in the motorized treadmill for a speed of 1.25 $m.s^{-1}$. Thus, once more, these results may suggest that the walking speed seems to be the main factor in the VO_2 differences between the different studies. However, the sample used in that study comprised young adults of both sexes (average age 27.4 ± 5.1 years), contrary to the current study.

The previous study with most similar methods compared with the current study, was that by Johnson and colleagues (2002). Percentage increases in VO_2 due to increases in slope in both studies revealed different magnitudes. It was found that when the slope increased from 0 to 5 % (32), or 6 % (this study), the increases in VO_2 were 39.5 and 47.7 %, respectively. A possible explanation for the largest increase observed in our study could be the difference in slopes, though small. However, when comparing slope increases between 0% and the highest slope (14 % in this study and 15 % in the study by Johnson et al. (32), the delta remained higher in our study (103.5 *vs* 90.8%). Therefore, other differences such as subjects' physical fitness may help to confront both studies.

Conclusions

This study extends the previous literature about the E during walking in field tracks, by including walking in different slopes and comparing it with walking at similar pace on a motorized treadmill. The results show that 1) VO_2, E and HR increase gradually with the slope of the route, both in the field and in the treadmill, 2) E and VO_2 are different in the two exercise conditions, being higher during treadmill walking at a similar pace. Therefore, our results suggest that the estimation of E in field tracks based on laboratory measurements can overestimate the true E.

References

1. Ainslie P, Campbell I, Frayn K, Humphreys S, Maclaren D, Reilly T. Physiological and metabolic responses to a hill walk. J Appl Physiol. 2002; 92:179-187.
2. Hoffman MD, Millet GY, Candau RB, Rouillon JD. Evaluation of a theoretical model to quantify the sources of metabolic cost in walking. Am J Phys Med Rehab. 2004; 83(5), May. 353-362.
3. Gottschall JS & Kram R. Energy cost and muscular activity required for propulsion during walking.2003 J Appl Physiol. 1985; 2003 May;94(5):1766-72.
4. Lovejoy CO. Evolution of human walking. Sci Am. 1988; 259, 118-125.
5. Sparrow WA, Newell KM. Energy expenditure and motor performance relationships in human learning a motor task. Psychophysiology. 1994; 31, 338-346.
6. Donelan JM, Shipman DW, Kram R, Kuo AD. Mechanical and metabolic requirements for active lateral stabilization in human walking. J Biomech. 2004; 37(6). 827-835.
7. Menz HB, Lord SR, Fitzpatrick RC. Acceleration patterns of the head and pelvis when walking on level and irregular surfaces. Gait Posture. 2003; 18, 35-46.
8. Hall C, Figueroa A, Fernhall B, Kanaley JA. Energy expenditure of walking and running: comparison with prediction equations. Med Sci Sport Exer. 2004; 36(12), 2128-2134.
9. Pearce ME, Cunningham DA, Donner AP, Rechnitzer PA, Fullerton GM, Howard JH. Energy cost of treadmill and floor walking at self-selected paces. Eur J Appl Physiol. 1983; 52(1), 115-119.
10. Alexander RM. Energetics and optimization of human walking and running: the 2000 Raymond Pearl Memorial lecture. Am J Hum Biol. 2002; 14, 641-648.
11. Bobbert AC. Energy expenditure in level and grade walking. J Appl Physiol. 1960; 15: 1015-1021
12. DeVoe D, Miller L, Gotshall R. Energy expenditure of backpacking for women on even and uneven terrain. Res Q Exercise Sport. 1998; 69(1), A32-33.
13. Caldwell GE, Van Emmerik REA, Hamill J. Movement proficiency: task demands and constraints. In: Sparrow, W. A. (Eds.). Energetics of human activity. Champaign, IL: Human Kinetics; 2000.
14. Patla AE, Sparrow WA. Factors that have shaped human locomotor structure and behavior. In Sparrow, W. A. (Eds.). Energetics of human activity. Champaign, IL: Human Kinetics; 2000.
15. DeVoe D. Caloric Expenditure During Backpacking. J Hum Movement Stud.

2001; 40, 259-268.
16. Di Prampero PE. The energy cost of human locomotion on land and in water. Int J Sports Med. 1986; 7, 55-72.
17. Murtagh EM, Boreham CA, Murphy MH. Speed and exercise intensity of recreational walkers. Prevention in Medicine. 2002; 35(4), 397-400.
18. Spelman C, Pate R, Macera C, Ward D. Self-selected exercise intensity of habitual walkers. Med Sci Sport Exer. 1993; 25(10), 1174-1179.
19. Elia M, Livesey G. Energy expenditure and fuel selection in biological systems: the theory and practice of calculations based on indirect calorimetry and tracer methods. World Revue of Nutrition Dietary. 1992; 70, 68-131.
20. Aisbett B, Le Rossignol P. Estimating the total energy demand for supramaximal exercise using the $\dot{V}O2$-power regression from an incremental exercise test. J Sci Med Sports. 2003; 6:343-347.
21. Box G EP. Some theorems on quadratic form applied to the study analysis of variance problems: II Effects inequality of variance and the correlation between errors in the TRo-way classification. Annals of Mathematical Statistics. 1954; 25, 484-498.
22. Bertram JEA, Ruina A J. Multiple walking speed-frequency relations are predicted by constrained optimization. A.J.of Theor. Biology. 2001; 209,445-453.
23. Falola JM, Delpech N, Brisswalter J. Optimization characteristics of walking with and without a load on the trunk of the body. Percept Motor Skill. 2000; 91, 261-272.
24. Margaria R. Sulla fisiologia e especialmente sul consumo energetico della marcia e della corsa a varia velocità ed inclinazione el terreno. Atti Accademia Nazionale dei Lincei. 1938; 7, 299-368.
25. Church TS, Earnest CP, Morss GM. Field tracks-testing of physiological responses associated with Nordic Walking. Res Q Exercise Sport. 2002; 73(3), 296-300.
26. Murray M, Spurr G, Sepic S, Gardner G, Mollinger L. Treadmill vs floor walking: kinematics, electromyogram and heart rate. J Appl Physiol. 1985; 59, 87-91.
27. Morgan DW, Martin PE, Krahenbuhl GS, Baldini FD. Variability in running economy and mechanics among trained male runners. Med Sci Sport Exer. 1991; 23(3), 378-383.
28. Morgan DW, Martin PE, Krahenbuhl GS. Factors affecting running economy. Sports Med. 1989; 7(5), 310-330.
29. Frishberg BA. An analysis of over ground and treadmill sprinting. Med Sci Sport Exer. 1983; 15, 478-485.
30. Elliott BC, Blanksby BA. A cinematographic analysis of overground and treadmill running by males and females. Med Sci Sport Exer. 1976; 8, 84-87.
31. Nelson RC, Dillman CJ, Lagasse P, Bickett P. Biomechanics of overground versus treadmill running. Med Sci Sport Exer. 1972; 4, 233-240.
32. Johnson A, Benjamin M, Silverman N. Oxygen consumption, heat production, and muscular efficiency during uphill and downhill walking. Appl Ergo. 2002; 33, 485-491.

Optimization as adaptability: how movement variability supports performance in striking actions used in combat sports

Dominic Orth[1], John van der Kamp[1], Robert Rein[2]

The functional role of movement variability: evidence in coordination and control

In this review, striking tasks derived from combat sports (including karate, Taekwondo, kung fu, boxing and mixed martial arts [MMA]) are evaluated to address the role of goal supportive or functional movement variability. Movement variability can be considered functional in so far that it ensures action goals are met by the individual, such as maintaining performance as constraints are changed (1).

Constraints specify the specific context of the action and can be further differentiated into individual, environmental and task constraints (1, 2). Constraints are understood as placing boundaries on movement coordination and control solutions (as opposed to proscribing them, (3)). Coordination solutions refer to distinctive patterns or classes of movement such as walking or running. The term control, a level of analysis embedded within the coordination of action, refers to movements made that regulate the stability of a given coordinative solution (4). Constraints define the space which the movement system can act (i.e., the perceptual-motor workspace) (5, 6), and as such determine what coordination solutions are available to maintain performance.

Previously, movement variability has (mistakenly) been conceptualized entirely as noise that needs to be reduced (7). However, more recent research has shown associations between movement variability and the maintenance of performance as constraints are changed (8). To exemplify, task constraints, might include goals or rules, such as strike a boxing bag with the hand as forcefully and efficiently as possible (9). The environmental constraints, on the other hand, include properties of the world external to the individual (10), and, might be the properties of the target and the distance to the target prior to executing a technique (11)

---

1. Faculty of Behavioral and Movement Sciences, Vrije Universiteit, Amsterdam, The Netherlands
2. Institute of Training and Computer Science in Sports German Sport University Cologne, Cologne, Germany.

(cf. (10)). As a general pedagogical strategy, by manipulating constraints, the individual can (learn to) exploit functional movement variability to maintain or improve performance when facing similar arrangements of constraints in the future (1, 3).

In striking tasks, there seems to be two levels at which functional movement variability is important (see Figure 1). On the one hand, individuals can use *movement variability* in terms of how they control a given action or technique. For example, when a kicking action is used, if a target is far away, the individual can increase the range of motion at the hips in order to kick it (12). On the other hand, individuals can use *behavioural variability*, by changing which coordination solution they realize to strike a target. For example, as the distance to a target is reduced, individuals might use a hook punch instead of a straight punch because the ability to generate sufficient force is afforded with the greater trajectory length permitted with a hook punch (9).

Within this context, affordances have been considered an additional source of constraint (13). Affordances refer to the behavioural opportunities that become available from the way the individual and their environment relate to each other during performance (14). The perception and realization of these affordances are reflected in the coordination solution used (e.g. crawling, walking, climbing (15)) and the way movement adjustments are made to satisfy constraints (15). For instance, in the case where individuals continue to realize an affordance under changing constraints, adaptive movements can be made to ensure that an affordance remains within the limit of achievability (16). For example in Orth et al. (17) soccer players running to cross a ball, were shown to modify the speed they ran based on the distance of an opposing player to the same ball. In this study, soccer players only ran close to their maximum running speed capabilities when the opponent was placed at a relatively close distance to the ball.

On the other hand, with larger changes in constraints, in cases where a different affordance is realized, a different coordination solution may arise. Warren (18), for instance, showed that the decision to change how to climb a stair, either in a bipedal fashion or a quadrupedal fashion, was predicted by the ratio between the stair riser height and the participants leg lengths. With larger increases in riser height, the same participant shifted to a different action. Whilst, there are different views on how affordances are perceived (for discussions see (16, 19)), the key implications are that, the coordination solution and the information used in order to achieve a certain objective (e.g., to get a ball before an opponent or to climb an object) is often based on the collective constraints of the individual and their environment, such that action capabilities (e.g., maximum running speed) and body dimensions (limb lengths) are scaled to properties of the environment when adapting behaviour.

Addressing individual differences in coordination and control in striking tasks

Consequently, when executing combat techniques, we assume that behaviour is controlled based on information that specifies whether or not the situation (e.g., the distance to a target or opponent) affords hitting such that it satisfies constraints (e.g., to impart a big impact). One of the promising features of striking tasks are in how previous work has addressed the influence of individual differences in body dimensions on the organization of striking actions (see (20), and Figure 1). Specifically, individual differences in body dimensions have been controlled for by scaling the distance between the individual and target (L) as a function of limb length (l), such that the scaled distance (D) is:

$$D_E = \frac{L}{l_E}$$

Equation 1.

Where the subscript $_E$ refers to the effector limb segments used in the scaling computation (typically either the leg, (11, 19) or arm, (9, 21)). By changing the distance to a target as function of limb length (i.e.,) the experimenter/practitioner can reduce the amount of between individual variability in terms of performance outcomes (11), regulatory movements (12) and techniques used (9).

In addition to addressing individual differences in body dimension, Hristovski, Davids, Araújo, and Passos, (22) proposed that body scaling be used as a way of manipulating the hypothetical workspace within which the individuals current behavioural capabilities can be determined. To exemplify, in the study by Hristovski, Davids, Araújo and Button, (9) individuals were positioned at 10 different distances from a free hanging boxing bag. At each position participants were asked to execute as many different techniques as possible (although limited to 10 strikes). It was shown that at some distances only two techniques (e.g., left and right hooks) might be used, whereas, at others, six might be used (i.e., left and right hooks, uppercuts and jabs). Thus, for linear changes in , participants either continued to use some techniques (perhaps by making small movements such as leaning in at the hips, (9)) or completely new actions emerged whilst others disappeared (see also Figure 1).

In this chapter, we explore how by comparing individuals across a range of positions their degree of functional movement variability bears a relationship to their skill. For example, an individual's current capabilities to produce a high impact collision for a given position might include a variety of techniques (such as a jab or a hook). This would indicate they have greater number of degenerate solutions for that set of constraints (23). Alternatively, for another individual, at the same position, they may only be able to effectively strike with a jab. However, this individual might be able to use the jab across a range of distances by modifying the way the technique is executed. In this context degeneracy, as a general property of complex systems and hallmark of skill and learning (24), reflects that the same outcomes can be achieved in different way. Practically speaking, prior to learning a new skill, the experimenter or practitioner can uncover an individual's pre-existing action repertoire and plan an intervention accordingly. Following the intervention, the same procedure can be used to determine how the individual's action repertoire is influenced by practice (25).

Skill effects can also be examined in a similar way (26). By fixing certain constraints (e.g., task goal), and manipulating others (e.g.,) a *scanning procedure* (see (27)) can be used for a variety of experimental and practical purposes. Figure 1 exemplifies how a scanning procedure can be carried out by determining an individual's ability to use punches and kicks to strike a bag over a range of position.

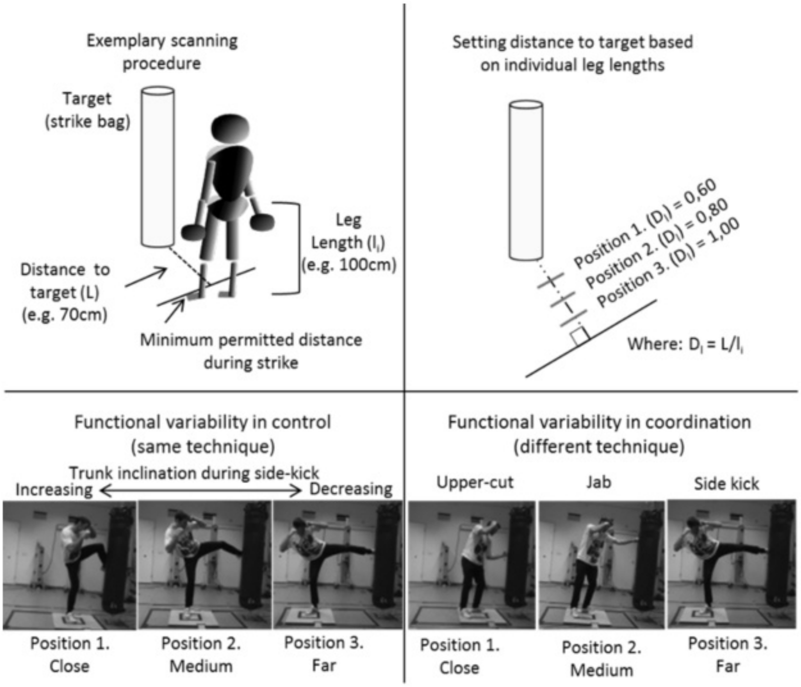


Figure 1. Upper left: task. Upper right: experimental paradigm for evaluating behavioural and movement variability. Bottom: example of different levels at which movement variability, including control (bottom left) and coordination (bottom right) that can emerge when changing the individual-target distance.

In this chapter we consider how functional movement variability, both in terms of movement variability within a specific technique (12, 21) and in terms of behavioural variability between techniques (20), might help individuals to maintain performance as constraints change. We focus on how individuals adapt to changes in the distance to a target (or the interpersonal-target distance) as this is most frequently researched. In doing so, we develop the hypothesis that experienced combat sportspeople can produce a greater range of techniques as constraints are manipulated *and* can maintain the effectiveness of any given technique over a larger range of interpersonal-target distances. Toward this end, there is a need to integrate the current research of striking actions with the hands and feet. Across the extant literature, numerous striking techniques have been examined when manipulating the interpersonal-target distance. However, techniques are typically examined separately, and with exception of Hristovsky et al. (9), are proscribed to the participant. Consequently, the functional role of variability at the within and between technique levels are poorly understood.

Thus, the aims of this chapter are: a) to evaluate how functional movement variability can be identified as a skilled response to variation in the interpersonal-target distance, and; b) to address implications for experimental and practice design. We begin, by detailing the current understanding of what constitutes an effective strike and how these are executed.

Determining functionality of striking actions

The assessment of effectiveness of striking actions is generally based on outcome measures including peak impact force (28), execution time (12), precision (29) and reaction-time (30). Impact force, in particular, has been a major focus of previous work where, impact force has proven to be significantly influenced by a range of variables (e.g., (31, 32)) and in particular skill level (33, 34). In this section, we present a framework for understanding how athletes of different skill level achieve an effective striking action. We do this by integrating a generalized muscle activation model (35) with models of how interceptive actions are regulated.

Generally, forces imparted to the stuck object, involves the transmission of momentum from the movement system, via the hand or foot, to the target mass (such as an opponent, force plate or bag). Because of the mechanical properties of the movement system (e.g., heterogeneous segmental dimensions and material properties), the transmission of forces is not equivalent to the mass of the system and its acceleration at impact (36, 37). To account for the expected force relative to the actual force imparted to the target, effective mass is used to reflect the capability (or relative efficiency) to transmit momentum (36). Specifically, effective mass is defined as the mass being used at impact (21, 38). To think of this intuitively, if a 5 kg weight is dropped to a (solid) floor, the effective mass will be around 5 kg. However, if we consider a 5 kg arm colliding with the same floor the effective mass will be less than 5 kg since the arm system is not rigid.

Effective mass is computed using the displacement (21, 34, 37) or impulse (29) of the struck object during collision relative to the speed of the effector immediately prior to collision (29, 34, 37). Effective mass is generally considered to be influenced by behaviour prior to collision (36, 38), such as the development of effector speed and/or timing of joint stiffening (35). Effector speed and effective mass, however, are not entirely correlated (29, 38, 39). For example, it has been reported that effector speed does not influence effective mass as much as the technique utilized (21) and both are considered important in determining the resultant peak impact force (29, 39).

In explaining the production of effective mass and hand speed, McGill et al. (35) put forward an empirically based model of a neuromuscular activation process involving three phases: the contract-relax-contract phases, a phenomenon also referred to as *double peak muscle activation* (36). McGill et al. (35) found that across a range of techniques, including punching and kicking, in some trunk and hip muscles there is firstly (phase 1); an initial burst of muscle activation associated with movement initiation, followed by (phase 2); a relaxation of muscle activity associated with production of effector speed, followed by (phase 3); a final burst of muscle activation associated with collision.

The initial burst of muscle activation (phase 1), occurring around movement initiation (35), is believed to provide a base of support (or inertial mass) from which the striking limb segments can rotate around or pull against (35, 40). Importantly, during the development of effector speed, previous work has highlighted the role of a proximal-to-distal sequencing (41), at least in some techniques (42, 43). Here, action is initiated by applying ground reaction forces (GRF) by the feet (40) and can include additional stepping movements that further increase GRF (29), or that provide postural stability (44). Lower limb strength and power measures, such as maximum isometric force and mean propulsive power in the squat, have also been correlated with peak impact force (45, 46). In any case, initial lower limb movements help to develop acceleration of hip and trunk rotations which can then be used by distal segments to develop end effector speed (35). For instance, there is some evidence that end effector speed during kicking is developed by an ordered sequencing of peak rotational accelerations around the hip and then knee, (42, 47). Similarly, this has also been shown in punching, with peak rotations first occurring at the shoulder, then elbow, then wrist (48).

The importance of the relaxation phase (phase 2) may be to prevent interference with the development of effector speed (35, 37). When muscles crossing a joint are stiffened, movement speed can paradoxically be reduced (39). Thus, maximizing the time over which certain muscles are relaxed can facilitate greater effector velocity. In terms of skilled striking then, following the initial muscle burst, there should be a rapid rate of relaxation (35). It has been argued that the period of relaxation should be extended for as long as possible such that reactivation (phase 3) occurs as close as possible in time relative to the collision. In both the trunk musculature and end effector limb, preparation for impact is particularly important to transmit both the GRFs through the body (41, 45) and the momentum developed by the end effector limb segment (39).

Roosen and Pain (49) also argued that athletes should attempt to have peak velocity and contact coincide. Yet, they found that in some strikes, peak velocity tended to occur prior to impact, see also (42). In support, VencesBrito et al. (28) showed that beginners reached forearm peak angular speed earlier than experienced individuals *and* tended to show a significantly earlier pronation at the forearms (corroborated in the timing of EMG activation), suggesting preparation for impact prior to collision and at least earlier than their more experienced counterparts. Similarly, Bolander et al. (21) examined differences between palm and fist strikes, finding that the largest forces were achieved with palm strikes. Also, 'small moments' were qualitatively observed around the wrist during punches, which seemed less important in the palm strike, improving the transfer of force in to the target with this way of striking. Finally, Kim et al. (42) observed the peak velocity and impact velocity of a range of kicking techniques in experts, showing that that peak velocity does not tend to coincide with the collision, further suggesting that stiffening occurs before impact.

Thus, an important ability seems to be to coordinate the development of effector speed with the onset of muscle stiffening, such that these movements are regulated with respect to the *timing* of the collision. The purpose of joint stiffening seems to be to transfer the momentum developed by the body into the object collided with, but, may also be balanced with the need to protect joints from strains/dislocations. In any case, pre-collision joint stiffening suggests information is exploited about when the impending collision will occur and used to optimize how hard the object is hit. This information is likely to be specific for the time remaining to contact (50, 51). From an affordance-based control perspective, where the individual scales behaviour based on their capabilities (16), we might speculate that if the task is to strike as hard as possible, individuals will scale when they begin to stiffen based on some physical limit, such as, speculatively, contractile velocity or a safety margin related to joint integrity.

In this section, we have identified a range of movements that can contribute to effector speed, such as the initial use of the feet or rotations at the trunk. These findings emphasize both, that the entire body (e.g., trunk, upper and lower limbs) is implicated in the optimization of impact forces (41, 45, 46, 52, 53) and that the timing of movements among limb segments relative to the collision event reflect an important control problem for how individuals are able to optimize impact forces (35, 36, 39).

Provided this general overview of what constitutes an effective striking action under ideal constraints (i.e., against stationary targets at self-preferred distances), we now consider how movement variability may help to maintain performance as conditions change, focusing on how individuals adapt to changes to the interpersonal-target distance.

The functional role of movement variability in striking performance

Within technique variability as a functional response to changes in constraints

Movement variability *during* execution of one particular technique can have goal supportive effects, even if this goal will often require low *outcome* variability such as high end-point accuracy (50, 54). For instance, changes in distance to the struck object prior to execution influences the mechanical properties (e.g., effector velocities (21), joint kinematics (12)) of the action. Effectiveness, such as impact force (21) and execution time (11, 19), can deteriorate when compared to a self-preferred distance (12, 45, 46). Alternatively, there is evidence that skilled individuals are better able to maintain performance effectiveness of a given technique over a larger range of interpersonal-target distances when compared to less experienced counterparts (11, 19). Taken together, these studies, summarized in Table 1, suggest that if individuals are able to functionally vary the mechanical properties of their movements for different execution distances, this can be adaptive to maintaining performance when using a particular technique.

Studies[1] [Participants]	Task description	Distance	Outcome measures[2]	Mechanics measured[2]
Bolander et al. (21) Moy Tung Ving Tsung martial artists (3 women, 10 men).	Ungloved maximal (force) strike (punch and palm tested) at a padded pendulum (eye and chest height tested).	1. Short (Hand length) 2. Medium (1/2 Arm length) 3. Long (Arm length)	Normalized peak acceleration Normalized peak impact force	NA

Estevan et al. (55) Taekwondo athletes (36 men [different weight effects tested]).	Strike (round-house kick) at head of human mannequin.	1. Short (0.68 ±0.05-m) 2. Normal (1.03 ±0.07-m) 3. Long (1.03 ±0.09-m) [scaled to leg length, details not reported]	Total response time (s) Peak impact (N) Body weight adjusted peak impact (N/kg)	NA
Estevan et al. (11) Taekwondo athletes (27 men [different skill groups tested]).	Maximal (strong and fast) strike (round-house kick) at chest of human mannequin.	1. Short: leg length x 0.67 (0.68 ±0.04-m) 2. Normal: leg length (1.01 ±0.06-m) 3. Long: leg length x 1.33 (1.35 ±0.09-m)	Execution time (s) Peak impact (N) Impact time (s)	NA
Falco et al. (19) Taekwondo athletes (31 [different skill groups tested]).	Maximal (force and speed) strike (round-house kick) at human mannequin (height = participants abdomen level).	1. Close: leg length x 0.67 2. Medium: leg length 3. Large: leg length x 1.33	Execution time (s) Peak impact (N)	NA
Kim et al. (12) Taekwondo athletes (12 men).	Maximal (effort) strike (round-house kick) at held pad (height = participants abdomen level).	1. Short (difference between Long and Normal [see 2 & 3]) 2. Normal (preferred distance) 3. Long (self-selected maximum)	NA	Total linear displacement of the hip (% leg length) Hip flexion (deg)* Pelvis rotation (deg)* * = only angles (degrees) reported as important given.
Loturco et al. (46) Elite amateur boxers (6 women, 9 men [gender effects tested]).	Gloved maximal (impact) strike (jab punch and cross punch tested) at a flat impact pad (perpendicular to the ground).	1. Self-selected 2. Imposed (arm length [no data])	Peak impact (N)	NA

Loturco et al. (45) Professional karate athletes (10 women, 9 men [gender effects tested]).	Gloved maximal (impact vs speed tested) strike (giaku-tsuki [aka. cross punch]) at sternum of human mannequin.	1. Self-selected 2. Imposed (length of the arm [no data])	Peak acceleration (g)	NA

1 = Studies delimited to those comparing performance across different distances. 2 = Not all outcome measures reported are presented. **g** = acceleration; **NA** = not applicable.

Table 1. Studies manipulating the target distance, and the outcome measures reported.

A number of studies have reported deterioration in performance outcomes in response to modified distances (45, 46). Loturco et al. (45), showed that at self-preferred distances, in professional karate athletes carrying out a maximal impact giku-tsuki (variation of the cross punch), higher impact forces were recorded compared to when they were required to punch at an imposed distance. Following this, Loturco et al. (46) went on to show that, at self-preferred distances, elite amateur boxers had higher impact forces for the jab technique than at an imposed distance. In support of these findings, Bolander et al. (21) observed impact force and hand accelerations across short (hand length), medium (about half the arm length) and long (arm length) distances to a target, finding that the largest forces and hand accelerations were associated with striking from the long distance. Similar findings have also been reported in strikes with the legs. Estevan et al. (55), for instance, observed impact forces and total response time for the roundhouse kick in Taekwondo athletes across short, normal and long distances. It was found that the shortest distance led to the highest peak impact forces and shortest total execution times. Using more or less the same protocol, Estevan et al. (11) and Falco et al. (19) also showed evidence of performance deterioration across three distances, an effect that was more pronounced in less skilled individuals.

By contrast, in other work, performance did not deteriorate as a function of changing the distance to the target (45, 46, 55). For example, Estevan et al. (55) reported that body weight might influence results. In this study, a range of weight categories were tested (58-68, 68-80 and >80 kg) across the three distances, reporting that participants from the welter weight group (68-80 kg) did not show any differences in terms of execution time or impact force. Loturco et al. (45) also did not find a reduction in cross punch performance when the task instructions were to maximize speed of the strike. In a later study, Loturco et al. (46) reported that performance deterioration was also influenced by technique. The cross punch did not significantly deteriorate in terms of impact force (46), although it did for the jab technique. One of the possible explanations for this discrepancy in findings is that the later study involved boxers and the former karate athletes. In competitive karate, the goal is to contact the opponent, and, striking with excessive force is penalized. In boxing, on the other hand, delivering damaging punches can indeed knock out the opponent to win. Thus, these findings allude to the effect of discipline specific experience on how individuals adapt to varying distances.

In any case, several studies have shown that skilled individuals appear able to avoid (some) significant performance deterioration as distances are either increased or decreased. Specifically, Estevan et al. (11) observed impact force, execution time and impact time in the roundhouse kick in Taekwondo athletes across three distances (short [0.67 x leg length], medium [leg length], and long [1.33 x leg length]). In this study two groups were compared based on skill: a group of athletes who had won a medal at official competitive level, versus a group whose members had not. Based on group-wise comparisons, no differences were identified in execution time or impact force at the medium distance between the groups. However, at the short and long distances, for both outcomes, the less skilled individuals were significantly worse than the more skilled group. In support, Falco et al. (19) examined the effect of distance to target and skill on maximal impact force and execution time when applying the roundhouse kick. Noting that distance was also scaled as a function of leg length, it was reported that there was no significant change in impact force across the three distances in the more skilled group, which consisted of individuals who had at least a medal at University or National level competition. In contrast, however, the less skilled group, which was made up of individuals who practiced the sport but had never won a University or National level competitive medal, showed significant differences in impact force (19). Falco et al. (19) did find however, that the skilled group showed slower execution times at the close distance and medium distances, indicating how, even in skilled individuals, some performance outcomes can deteriorate whilst others can be maintained as constraints are changed.

Only one study (12) could be found to contrast the kinematics of techniques as the target distance was modified. Thus, there is limited insight into the adaptive adjustment in movements (i.e., execution variability) occurring during the performance of specific techniques that might help skilled individuals maintain low performance or outcome variability as constraints change. Kim et al. (12) examined the effect of three distances to a target on kinematics of the trunk, hip and kicking leg when applying the roundhouse kick in experienced Taekwondo athletes. In this study, kinematic variables at different movement (including push [start signal to toe-off], release [toe-off to maximum knee flexion to impact] and striking phases [maximum knee flexion to impact]) were examined. Increased kick distance seemed to be achieved by increased pivot hip displacement (i.e., the leg supporting the body weight displaced toward the target). Pivot hip displacement appeared to be regulated on the basis of degree of body posture during the strike (i.e., leaning back such that the trunk becomes more parallel with the ground) and pivot foot rotation (12). Specifically, when going from short to long distances, the pelvic posterior tilt and left rotation increased, whilst both the hip flexion and the trunk´s right lateral tilt decreased (i.e., indicating they were leaning back) (12). This suggests that controlling the reach of the foot to the target is achieved by coupling the pelvis and kicking leg, *and*, pelvis and trunk movements. During the strike phase, these couplings are believed to be particularly important for adapting to the degree of pelvis displacement during the push and release phases (12, 42).

In summary, there is clear evidence that changing the distance to the target can lead to performance deterioration (45, 46). In addition, there is some evidence that skilled individuals better maintain performance as the distance is manipulated (11, 19). There is also the possibility that, some outcome parameters might deteriorate whilst other outcomes can be maintained, such as execution time being maintained at the expense of peak impact force (11, 19). Finally, the kinematics of an action or technique are also influenced by changing the distance to the target (12). Although there is no direct evidence that this sort of movement variability supports the ability to maintain performance, in terms of impact force or execution time, it can be said to at least support general task success of hitting the target (12).

There is a dire need for future research to establish how movement variability allows individuals to maintain performance of a technique as conditions are modified. Indeed, this question is similar to Bernstein's problem raised in his work on kinematic trajectories of the arm of blacksmiths (56). During hammering iron, Bernstein showed that blacksmiths while hammering, although they would move using different trajectories, they maintained very effective precision and impact.

The role of between technique variability for supporting performance

Whilst the above section focused on evidence for functional movement variability as supporting performance when using *the same technique*, another feature of striking tasks is the possibility to use different techniques. Presumably, in combat sports, one of the reasons different methods of striking have emerged (e.g., hooks, jabs and side-kicks) is because under different conditions, such as being relatively closer or further to a target, one technique can be more effective than others. As an example, if the distance to a target is greater than the ability to reach it with a punch, the individual must switch to using a leg technique to meet the objective of striking the target. Other reasons can also be identified, for instance the nature of an opponent's guard might mean that a strike moving primarily through the anteroposterior axis (e.g., a cross or jab, (31)) is easily blocked and a curved trajectory would be more successful (9, 31). Indeed, techniques qualitatively differ, and it is usually based on the nature of the end effectors trajectory *relative* to the target that techniques have been classified. For example, a hook punch and upper-cut move along different axes (i.e., left-right and craniocaudal respectively), but at the same time both have a curved trajectory (9, 31, 57) and can conceivably show similar functional angles.

In this section, we review the evidence that shifting between techniques in response to a modified distance between the participant and the struck object, prior to executing the action, can help maintain or even improve performance (i.e., is a functional response). In striking tasks some evidence for this has been uncovered by comparing the relative effectiveness of techniques across different distances. For example, in punching techniques, whilst the straight punch might produce the largest impact force, at least in (49, 53, 58), when participants are positioned at relatively close interpersonal-target distance, this technique does not emerge as a preferred choice (9). These findings highlight the possibility that to maintain performance across distances, individuals also have the option of changing techniques (9, 21, 46, 57).

In Bolander et al. (21), hand speed and impact force were compared between punch and palm strikes across three distances (short, medium and long). The results showed that both techniques produced the best performances at the long distances. Similarly, Loturco et al. (46) compared the impact forces of jabs and crosses at a self-preferred distance and at an imposed distance (the length of each individuals arm at full extension). Notably the jab performance was worse at the imposed distance, whereas in the cross there were no differences based on distance. Unfortunately, the self-preferred distances were not reported and thus, a reason for this technique by distance interaction might be that the self-selected and imposed distances were very similar for the cross but very different in absolute terms for the jab. Alternatively, as suggested by the authors, it is possible that the cross is more effective over a larger range of distances. According to the authors, the cross is primarily a technique practiced to achieve high impact, whereas, the jab is a technique primarily used, not for maximal force, but to prepare for other strikes (e.g., used to 'open up' the opponent).

Supporting the idea that individuals have a self-preferred distance from which they apply different techniques, an innovative work by Petri et al. (57) showed that at key times (i.e., the hypothetical time needed to respond to a visual stimulus), experienced karate athletes actively regulate the distance from which attacks are initiated based on the technique being used. Specifically, the jab and reverse punches tended to be initiated from similar inter-personal distances whereas the roundhouse kick was initiated at a greater inter-personal distance. This study seems to suggest the performers actively regulated their interpersonal distance to ensure that a particular technical action remained possible (59).

More challenging to explain are the findings in Hristovski et al. (9). They suggest that conditions of maximum overlap of possible actions exist that correspond to the most functional region of performance. That is, at certain regions multiple actions can be equi-functional reflecting performance meta-stability. Hristovski et al. (6) conjectured that the more extensive this region, the greater the individual's skill, see also (24). Currently, Hiristovski et al. (9), is the only study identified to examine conditions where individuals had freedom to select techniques. To recall, Hristovski et al. (9), had equally skilled individuals (beginner boxers) placed at 10 equally spaced distances from a heavy bag (beginning with both toes touching the bag, and ending with both toes at an absolute distance of 1 m). At each position, participants could strike the bag 10 times and were encouraged to vary the techniques they applied. Specifically, they were encouraged to use different techniques so long as they could do so forcefully, with postural stability, and with the perception of movement efficiency. At small values of D_a (~0-0.1) (D_a = absolute distance to the bag/individuals arm length), only left and right hooks were selected. At small-moderate values of D_a (~0.1-0.5), both left and right hooks and left and right upper cuts emerged. At moderate values of D_a (~0.5-0.9), left and right hooks, left and right upper cuts and left and right jabs emerged. At large values of D_a (1-1.2) only left and right jabs emerged. Finally, at values of D_a greater than 1.2, participants were inactive, unable to reach the target.

According to Hristovski et al. (9) the distance where D_a was between 0.5 and 0.9, corresponded to the highest levels of efficiency (for the striker) and uncertainty (for a hypothetical opponent). It is the region of meta-stability. A limitation in Hristovski et al. (9) is that '…efficiency was scaled by participants on a 6-point (0-5) continuous scale with 0 reflecting absence of a stroke and 5 signifying a maximally efficient stroke.' This makes it difficult to determine what specifically was influencing the boxer's decisions when using strikes at various distances, and, whether indeed when striking actions overlapped performance was maintained. There is however, evidence that being able to use more techniques in a randomized fashion does make it more difficult for opponents to predict which technique will be used in advance of execution (60). Presumably, the more techniques an individual can exhibit, the greater opportunity they have to induce uncertainty in their opponent.

In sum, in this section we have used the interpersonal-target distance as a parameter to examine the importance of between technique variability for maintaining performance. In general, the ability to appropriately shift between techniques with respect to variations in the interpersonal-target distance seems to be pertinent for skilled combat sport athletes (57). Future research should, however, uncover clearer evidence that a greater variety of techniques is associated with improved skill. For example, examining skill effects in a task similar to Hristovksi et al. (9) should reveal that more experienced individuals can demonstrate a larger number of techniques and maintain them over a larger range of distance (i.e., they show a greater region of meta-stability). The main challenge in such a study is to assess the functionality of strikes in an 'unconstrained' setup (i.e., where the individual can strike at different angles and positions – for some innovative approaches see (61, 62)).

Implications that increased movement variability supports performance

A key implication of this review is that individuals able to use a given striking technique effectively over a broader range of constraint manipulations *and* able to use more techniques overall, should be more capable of adapting to changes in conditions. This would suggest that during practice, arranging constraints to induce greater movement variability may be beneficial to the learner (63, 64). It is, however, unclear to what extent increased practice variability helps individuals to perform effectively in new contexts and also to what extent the purported effect of practice variability would be modulated by skill. For example, an individual who learns to effectively apply a roundhouse kick over a broad range of conditions is placed in a situation where they cannot use this kick, may or may not have problems adapting another technique in its place. The same empirical questions could be raised for an individual who practices a range of different techniques (see for example the discussion in Ranganathan and Newell (65) on execution redundancy verse task variation).

Another possibility that has not been considered, is that exploratory behaviour, where the individual may aim to learn about theirs and their opponent's capabilities under a particular set of constraints can also be useful for performance (66). Sève et al. (66) for example showed that in table tennis, skilled players went through an 'enquiry phase', exploring the effectiveness of different performance actions through adopting a variety of different types of shots, in order to learn about the opponent's weaknesses, strengths and strategies. Following this period of *exploration* (behaviour that was primarily directed toward information gathering), players settled to a phase of *performance*, where 'players seek optimal playing effectiveness by reproducing the strokes they identify as perturbing to the opponent…' In paraphrasing Sève et al. (66), exploration was found to be important to all performers across all competitive match-ups, even in cases where the individual knew the opponent, as they could not rely on predicting the events of a current match due to how features of an opponent's game differ within and across matches. A possibility is that increased functional movement variability, between and within techniques, allows the individual to explore new competitive match-ups.

Taken together, this review implies that the coach or experimentalist can, and perhaps should, modify constraints (i.e., in the task and/environment) during practice with the aim of increasing functional movement variability (and which may include their capabilities to explore in support of the overall task goal, (67)). In doing so, the learner may increase their capability to adapt and learn under new constraints, rather than optimize a technique according to some idealized standard (68).

Conclusions

We have developed the argument that increased movement variability at the within and between levels of action can help individuals maintain performance as conditions are modified. Functionality in striking actions involves a balance of developing speed in the end-effector with accurate timing of movements, including well timed joint stiffening, relative to the moment of impact. Different methods of striking, such as cross punches or side-kicks, afford the individual different ways of hitting a target, including in terms of different locations and also different trajectories (such a curved or straight, and which may be targeted at different or the same location). Furthermore, sensitivity to the information, at least in terms of interpersonal-target distance, for perceiving the boundaries within which techniques are effective also seems to be a capability of skilled individuals. When dealing with opponents, the ability to use multiple attack methods in randomized fashion can also help inhibit the opponent's capacity to predict actions in advance. These predictions can be tested using experimental procedures similar to those reported in Hristovski et al. (9). Other predictions have also been developed, and include that individuals with greater functional movement variability, either at within or between technique levels, can adapt effectively to new constraints (unfamiliar task and environmental manipulations). We also argue that, during practice, interventions that increase functional movement variability may be beneficial, however, future research needs to address these questions experimentally.

References

1. Davids K, Glazier P, Araújo D, Bartlett R. Movement systems as dynamical systems: The functional role of variability and its implications for sports medicine. Sports Medicine. 2003;33(4):245-60.
2. Newell KM. Constraints of the development of coordination. In: Wade MG, Whiting HTA, editors. Motor Development in Children: Aspects of Coordination and Control. Dordrecht: Martinus Nijhoff Publishers; 1986.
3. Renshaw I, Chow JY, Davids K, Hammond J. A constraints-led perspective to understanding skill acquisition and game play: A basis for integration of motor learning theory and physical education praxis? Physical Education and Sport Pedagogy. 2010;15(2):117-37.
4. Newell KM. Change in movement and skill: Learning, retention, and transfer. In: Latash ML, Turvey MT, editors. Dexterity and its Development. New Jersey: Psychology Press; 1996. p. 393-429.
5. Sporns O, Edelman GM. Solving Bernstein's problem: A proposal for the development of coordinated movement by selection. Child Development. 1993;64(4):960-81.
6. Newell KM, Liu YT, Mayer-Kress G. A dynamical systems interpretation of

epigenetic landscapes for infant motor development. Infant Behavior and Development. 2003;26(4):449-72.
7. Riley MA, Turvey MT. Variability and determinism in motor behavior. Journal of Motor Behavior. 2002;34(2):99-125.
8. Chow JY, Davids K, Hristovski R, Araújo D, Passos P. Nonlinear pedagogy: Learning design for self-organizing neurobiological systems. New Ideas in Psychology. 2011;29(2):189-200.
9. Hristovski R, Davids K, Araújo D, Button C. How boxers decide to punch a target: Emergent behaviour in nonlinear dynamical movement systems. Journal of Sports Science and Medicine. 2006;CSSI:60-73.
10. Newell KM, Jordan K. Task constraints and movement organization: a common language. In: Davis WE, Broadhead GD, editors. Ecological task analysis and movement. Champaign, IL: Human Kinetics; 2007. p. 5-23.
11. Estevan I, Álvarez O, Falco C, Molina-García J, Castillo I. Impact force and time analysis influenced by execution distance in a roundhouse kick to the head in Taekwondo. The Journal of Strength & Conditioning Research. 2011;25(10):2851-6.
12. Kim JW, Kwon MS, Yenuga SS, Kwon YH. The effects of target distance on pivot hip, trunk, pelvis, and kicking leg kinematics in Taekwondo roundhouse kicks. Sports Biomechanics. 2010;9(2):98-114.
13. Riccio GE, Stoffregen TA. Affordances as constraints on the control of stance. Human Movement Science. 1988;7(2):265-300.
14. Gibson JJ. The ecological approach to visual perception. Boston: Houghton Mifflin; 1979.
15. Warren WH. The dynamics of perception and action. Psychological Review. 2006;113(2):358-89.
16. Fajen BR. Affordance-based control of visually guided action. Ecological Psychology. 2007;19(4):383-410.
17. Orth D, Davids K, Araujo D, Renshaw I, Passos P. Effects of a defender on run-up velocity and ball speed when crossing a football. European Journal of Sport Science. 2014;14(sup1):S316-S23.
18. Warren WH. Perceiving affordances: Visual guidance of stair climbing. Journal of Exerimental Psychology: Human Perception and Performance. 1984;10(5):683-703.
19. Falco C, Alvarez O, Castillo I, Estevan I, Martos J, Mugarra F, et al. Influence of the distance in a roundhouse kick's execution time and impact force in Taekwondo. Journal of Biomechanics. 2009;42(3):242-8.
20. Hristovski R, Davids K, Araújo D. Affordance-controlled bifurcations of action patterns in martial arts. Nonlinear Dynamics, Psychology, and Life Sciences. 2006;10(4):409-44.
21. Bolander RP, Neto OP, Bir CA. The effects of height and distance on the force production and acceleration in martial arts strikes. Journal of Sports Science and Medicine. 2009;8(3):47-.
22. Hristovski R, Davids K, Araújo D, Passos P. Constraints-induced emergence of functional novelty in complex neurobiological systems: A basis for creativity in sport. Nonlinear Dynamics, Psychology, and Life Sciences. 2011;15(2):175-206.
23. Mason PH, Winter B, Grignolio A. Hidden in plain view: degeneracy in com-

plex systems. Biosystems. 2015;128:1-8.
24. Davids K, Araújo D, Seifert L, Orth D. Expert performance in sport: An ecological dynamics perspective In: Baker J, Farrow D, editors. Routledge Handbook of Sport Expertise: Routledge; 2015. p. 130-44.
25. Komar J, Chow JY, Chollet D, Seifert L. Effect of analogy instructions with an internal focus on learning a complex motor skill. Journal of Applied Sport Psychology. 2014;26(1):17-32.
26. Seifert L, Leblanc H, Chollet D, Delignières D. Inter-limb coordination in swimming: effect of speed and skill level. Human Movement Science. 2007;29(1):103-13.
27. Kostrubiec V, Zanone PG, Fuchs A, Kelso JAS. Beyond the blank slate: routes to learning new coordination patterns depend on the intrinsic dynamics of the learner: Experimental evidence and theoretical model. Frontiers in Human Neuroscience. 2012;6:1-14.
28. VencesBrito AM, Ferreira MAR, Cortes N, Fernandes O, Pezarat-Correia P. Kinematic and electromyographic analyses of a karate punch. Journal of Electromyography and Kinesiology. 2011;21(6):1023-9.
29. Neto OP, Silva JH, de Miranda Marzullo AC, Bolander RP, Bir CA. The effect of hand dominance on martial arts strikes. Human Movement Science. 2012;31(4):824-33.
30. Martinez de Quel O, Bennett SJ. Kinematics of self-initiated and reactive karate punches. Research Quarterly for Exercise and Sport. 2014;85(1):117-23.
31. Piorkowski BA, Lees A, Barton GJ. Single maximal versus combination punch kinematics. Sports Biomechanics. 2011;10(1):1-11.
32. Joch W, Fritsche P, Krause I. Biomechanical analyses of punching in boxing. In: Morecki A, Fidelius K, Kedzior K, Wit A, editors. Biomechanics VII-B. 3 B. Baltimore: University Park Press; 1981. p. 343-9.
33. Smith MS, Dyson RJ, Hale T, Janaway L. Development of a boxing dynamometer and its punch force discrimination efficacy. Journal of sports sciences. 2000;1(6):445-50.
34. Neto OP, Magini M, Saba MM. The role of effective mass and hand speed in the performance of kung fu athletes compared with nonpractitioners. Journal of Applied Biomechanics. 2007;23(2):139-48.
35. McGill SM, Chaimberg JD, Frost DM, Fenwick CM. Evidence of a double peak in muscle activation to enhance strike speed and force: an example with elite mixed martial arts fighters. The Journal of Strength & Conditioning Research. 2010;24(2):348-57.
36. Lenetsky S, Nates RJ, Brughelli M, Harris NK. Is effective mass in combat sports punching above its weight? Human Movement Science. 2015;40:89-97.
37. Walilko TJ, Viano DC, Bir CA. Biomechanics of the head for Olympic boxer punches to the face. British Journal of Sports Medicine. 2005;39(10):710-9.
38. Blum H. Physics and the art of kicking and punching. American Journal of Physics. 1977;45(1):61-4.
39. Pain MT, Challis JH. Soft tissue motion during impacts: Their potential contributions to energy dissipation. Journal of Applied Biomechanics. 2002;18(3):231-42.

40. Cheraghi M, Alinejad HA, Arshi AR, Shirzad E. Kinematics of straight right punch in boxing. Annals of Applied Sport Science. 2014;2(2):39-50.
41. Lenetsky S, Harris N, Brughelli M. Assessment and contributors of punching forces in combat sports athletes: Implications for strength and conditioning. Strength & Conditioning Journal. 2013;35(2):1-7.
42. Kim YK, Kim YH, Im SJ. Inter-joint coordination in producing kicking velocity of Taekwondo kicks. Journal of Sports Science & Medicine. 2011;10(1):31-8.
43. Preuschl E, Hassmann M, Baca A. A Kinematic Analysis of the Jumping Front-Leg Axe-Kick in Taekwondo. Journal of Sports Science & Medicine. 2016;15(1):92-101.
44. Cesari P, Bertucco M. Coupling between punch efficacy and body stability for elite karate. Journal of Science and Medicine in Sport. 2008;11(3):353-6.
45. Loturco I, Artioli GG, Kobal R, Gil S, Franchini E. Predicting punching acceleration from selected strength and power variables in elite karate athletes: A multiple regression analysis. The Journal of Strength & Conditioning Research. 2014;28(7):1826-32.
46. Loturco I, Nakamura FY, Artioli GG, Kobal R, Kitamura K, Abad CCC, et al. Strength and power qualities are highly associated with punching impact in elite amateur boxers. The Journal of Strength & Conditioning Research. 2016;30(1):109-16.
47. Tang WT, Chang JS, Nien YH. The kinematics characteristics of preferred and non-preferred roundhouse kick in elite Taekwondo athletes. Journal of Biomechanics. 2007;40(S780).
48. Nakano G, Iino Y, Imura A, Kojima T. Transfer of momentum from different arm segments to a light movable target during a straight punch thrown by expert boxers. Journal of Sports Sciences. 2014;32(6):517-23.
49. Roosen A, Pain MTG. Impact timing and stretch in relation to foot velocity in a taekwondo kicking combination. Journal of Biomechanics. 2006;39(S1):562.
50. Lee DN, Lishman JR, Thomson JA. Regulation of gait in long jumping. Journal of Experimental Psychology: Human perception and performance. 1982;8(3):448-59.
51. Caljouw SR, van der Kamp J, Savelsbergh GJ. Timing of goal-directed hitting: Impact requirements change the information–movement coupling. Experimental Brain Research. 2004;155(2):135-44.
52. Filimonov VI, Koptsev KN, Husyanov ZM, Nazarov SS. Boxing: Means of increasing strength of the punch. Strength & Conditioning Journal. 1985;7(6):65-6.
53. Turner A, Baker ED, Miller S. Increasing the impact force of the rear hand punch. Strength & Conditioning Journal. 2011;33(6):2-9.
54. Scott MA, Li FX, Davids K. Expertise and the regulation of gait in the approach phase of the long jump. Journal of Sports Sciences. 1997;15(6):597-605.
55. Estevan I, Falco C, Álvarez O, Molina-García J. Effect of Olympic weight category on performance in the roundhouse kick to the head in taekwondo. Journal of Human Kinetics. 2012;31:37-43.
56. Bernstein NA. The co-ordination and regulation of movements. London,

England: Pergamon; 1967.
57. Petri K, Lichtenstein M, Bandow N, Campe S, Wechselberger M, Sprenger D, et al. Analysis of anticipation by 3D motion capturing–a new method presented in karate kumite. Journal of Sports Sciences. 2017;35(2):130-5.
58. Bartsch A, Benzel E, Miele V, Morr D, Prakash V. Impact 'fingerprints' and preliminary implications for an 'intelligent mouthguard'head impact dosimeter. Sports Engineering. 2012;15(2):93-109.
59. Dicks M, Davids K, Button C. Individual differences in the visual control of intercepting a penalty kick in association football. Human Movement Science. 2010;29(3):401-11.
60. Milazzo N, Farrow D, Ruffault A, Fournier JF. Do karate fighters use situational probability information to improve decision-making performance during on-mat tasks? Journal of Sports Sciences. 2016;34(16):1547-56.
61. Buśko K, Staniak Z, Szark-Eckardt M, Nikolaidis PT, Mazur-Różycka J, Łach P, et al. Measuring the force of punches and kicks among combat sport athletes using a modified punching bag with an embedded accelerometer. Acta of Bioengineering and Biomechanics. 2016;18(1):57-4.
62. Pierce JD, Reinbold KA, Lyngard BC, Goldman RJ, Pastore CM. Direct measurement of punch force during six professional boxing matches. Journal of Quantitative Analysis in Sports. 2006;2(2):1-18.
63. Schöllhorn WI, Mayer-Kress G, Newell KM, Michelbrink M. Time scales of adaptive behavior and motor learning in the presence of stochastic perturbations. Human Movement Science. 2009;28(3):319-33.
64. Chow JY, Davids K, Button C, Shuttleworth R, Renshaw I, Araújo D. The role of nonlinear pedagogy in physical education. Review of Educational Research. 2007;77(3):251-78.
65. Ranganathan R, Newell KM. Changing up the routine: Intervention-induced variability in motor learning. Exercise and Sport Sciences Reviews. 2013;41(1):64-70.
66. Sève C, Saury J, Ria L, Durand M. Structure of expert players' activity during competitive interaction in table tennis. Research Quarterly for Exercise and Sport. 2003;74(1):71-83.
67. Seifert L, Boulanger J, Orth D, Davids K. Environmental design shapes perceptual-motor exploration, learning, and transfer in climbing. Frontiers in Psychology. 2015;6:1819.
68. Carroll TJ, Riek S, Carson RG. Neural adaptations to resistance training. Sports Medicine. 2001;31(12):829-40.

The use of power output in road cycling to optimize training and establish performance

Alejandro Javaloyes[1], José Manuel Sarabia[1] and Manuel Moya-Ramón[1]

Introduction

Road cycling is an endurance sport characterized by a high volume at low and moderate intensities and specific moments of high intensity in both, training and racing situations (1). The duration of races is variable, from 4 km of a time-trial to more than 250 km of a road race. In addition, competitions range from one-day (e.g. Spring classics, World Championships) to three-week competitions (e.g. Tour of France). Intensity is dependent on several factors, such as tactics, type of stage and the cyclist's role, making road cycling a sport that is stochastic in nature (2, 3). In road cycling, there are two types of stages: On the one hand, individual and team time-trial and on the other hand, mass-start races with flat, middle mountain and high mountain profile, according to distance riding uphill (1). Professional riders cycle around 35.000 km during training and races in a whole season with a range of 70 to 90 days of competition. Furthermore, there is a specialist for any type of race and with different functions inside a team. There are five rider types, each with their own anthropometric characteristics and physiological variables (4): flat terrain riders, uphill riders, all terrain riders, time-trial specialist and sprinters. Therefore, regardless their speciality, cyclists must be able to perform in a wide range of intensity and duration of efforts. Due to these characteristics, training and racing control is the main objective to achieve the best performance during the most part of the season. In recent years, there has been a huge development of power meters. These devices are fitted on the bike and allow to measure power output continuously during both, race and training. Power output is an external measure of the intensity of effort obtained from the force applied to the pedal, and the angular velocity with which this force is applied.

Performance in this type of sport is established by several factors: aerobic performance, anaerobic performance, and efficiency (5). Therefore, these factors regulate the response to training load and competi-

---

1. Sports Research Centre, Universidad Miguel Hernandez de Elche, Elche, Spain

tion in the cyclist. This book chapter focused on the aerobic performance and the ability of power output to monitor it. The two main parameters derived from the aerobic performance are maximal oxygen uptake (VO_2max) and anaerobic thresholds (lactate or ventilatory threshold, LT or VT, respectively). In addition, methodologies to establish these parameters based on power output in both, laboratory and field situations are presented below.

Optimizing training and racing through power output

In the last decade, the use of power output to measure intensity in cycling has increased its popularity. This is because low-cost and high reliable power meters have begun to be commercialized (3). This fact allows most cyclists (professional or amateur) to be able to attach these devices on their bikes. Power output is a measure of external load, providing an intensity of effort instantly, in contrast to internal load measurements like heart rate (HR) (2), that represents a body's response to the intensity (internal load). Although HR was the most used variable and considered the gold-standard parameter to control intensity in endurance sports during the past decade, there are many disadvantages derived from its use (6). For example, HR is modified by many external factors that are not related to training, such as environmental conditions, mood state, intake of certain substances like caffeine etc., and the 'physiological lag' inherent to HR.

However, power output presents difficulties in its analysis due to the variability presented by the power values. Due to this, having techniques that we can use to record and analyse is essential to interpret the data correctly, obtaining conclusions about the performance of cyclists from a single training or race to a full competition season. Furthermore, the analysis of power output during long periods is a tool that enables cycling teams to evaluate weaknesses and strengths of their cyclists and could be used to select the best cyclists for each type of race or competition.

Mean Power Output

The use of mean power output of a single session provides an average measurement of the effort. Although this reduction to a single number is attractive, the main problem of this variable is that road cycling is mainly a sport with a high variability in intensity, with long periods of low and moderate intensities and specific moments of high intensity (Figure 1). Two different training sessions with the same mean power could have a different impact on the cyclist. For example, a continuous training session of one hour at 200 W session could have as a result the same mean power output as one hour performing bouts of one minute at 400 W and another minute of passive recovery (i.e. 0 W), both cases with a mean power of 200 W. However, the impact of each training session will be very different.

Normalized Power Output

To solve this problem and taking into account the facilities of using a single number, Allen and Coggan (7) proposed the use of normalized power output. Normalized power output is a fourth power-weighted 30-second moving average. The choice of 30-second windows is based on many physiological processes, like heart rate, which response is around this period of time (2, 7). During homogeneous training sessions, mean power output and normalized power output remain at the same or similar values but in training sessions with high variability in power output, normalized power output increases in function of time at the higher intensities (Figure 1). Nevertheless, normalized power output seems to overestimate the intensity of effort (8) and further research is needed to establish the usefulness of this metric.

Variability of Power Output

Due to the stochastic nature of cycling, a high variability in intensity, and consequently in power output is produced in road cycling. However, this variability is dependent on the type of race or training. For example, a flat 40 km Time-Trial could lead to a low variability in power output, but a high mountain stage, with long up and down hills, has large variability in power output. There are many procedures to evaluate variability in any type of signal, including power output in cycling. Exposure Variation Analysis (9) is a model that takes different efforts and their duration into account. This model has been adapted to cycling (10). Another easy option to evaluate variability in power output is the normalized power output: mean power output ratio, also called Variability Index (7). Values close to 1 indicate a low variability, on the other hand, the further away from 1 the greater the variability of power output (Figure 1).

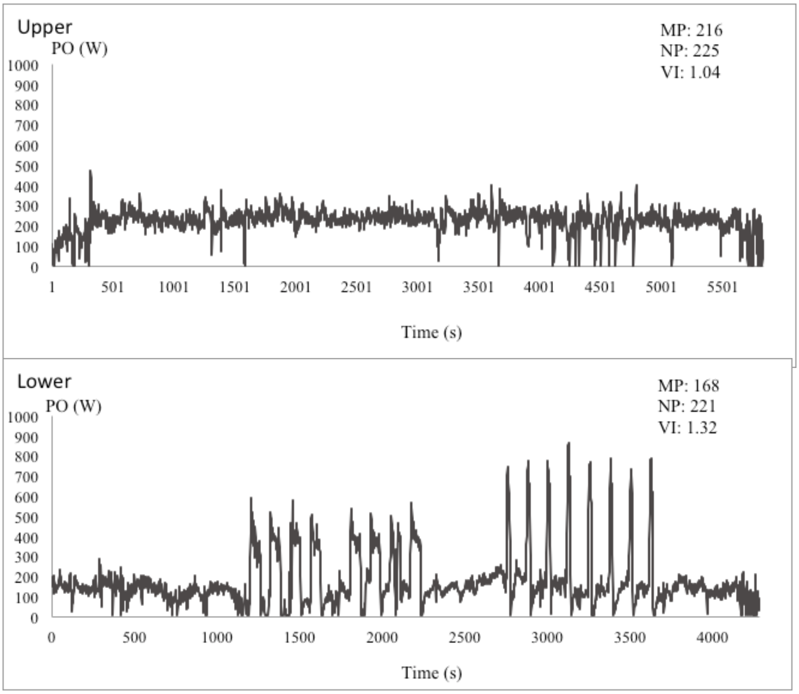


Figure 1. Power output during two different type of training sessions: Continuous training session at a constant workload (Upper panel) and Intervallic training session with sets of high intensity followed by periods of recovery between sets (Lower panel).

Record Power Profile

Another option to visualize power data and its distribution is to organize it in maximal mean power in function of time. The Record Power Profile, proposed by Pinot and Grappe (11) is one of the best methods to establish the relationship Power Output-Time. Record Power Profile records best power outputs in different time intervals from 1 s to 4 h in both, absolute power output (W) and relative power output to body weight (W/kg) (Figure 2, upper panel). Record Power Profile was proposed for monitoring long periods and could be used to track changes in performance, for example an improvement in the power output in different duration of effort (figure 2, lower panel), to establish a cyclist's characteristics and to detect possible weaknesses.

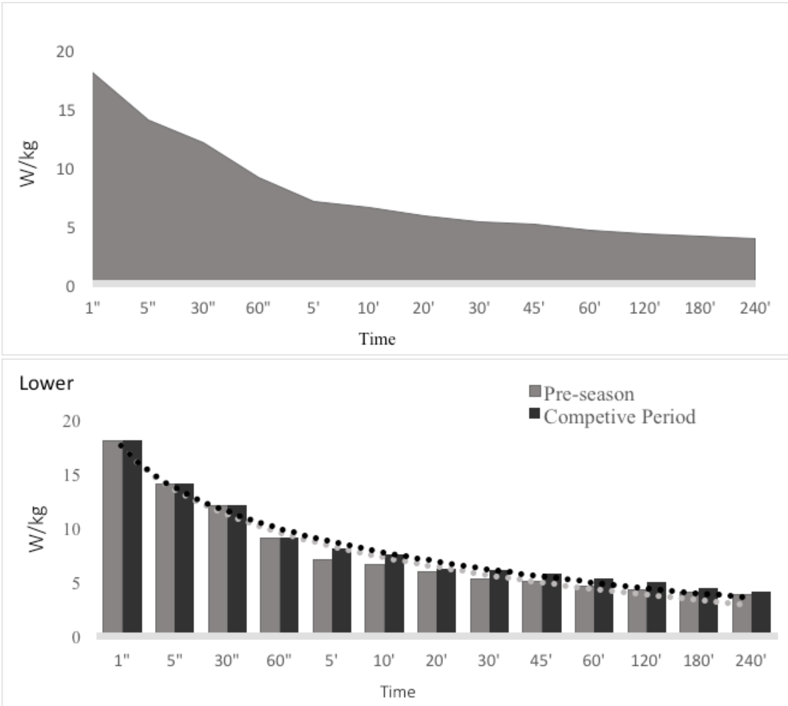


Figure 2. Individual Record Power Profile of a professional cyclist (upper) and its changes in RPP according to the period of the season (lower).

Methodologies to establish aerobic performance in cycling

Maximal Aerobic Capacity: Maximal Oxygen Uptake and Maximal Aerobic Power

Maximal oxygen uptake (VO_{2max}) is defined as the maximal capacity of an organism to extract and consume O_2 (Fernandez-Vaquero, 2008). VO_{2max} has been considered one of the factors that determinate performance in endurance sports. However, after 5 – 8 min at VO_{2max} intensity there is a drop in systolic volume, an acceleration of fatigue, a reduction in the oxygen uptake and an increase in the anaerobic metabolism to produce energy (12). Therefore, during a 40 to 80 km Individual Time-Trial the intensity is around 75 -85 % of VO_{2max} while in shorter efforts (e.g. a 4 km Time-Trial) the intensity is closer to VO_{2max}. This fact does not invalidate the importance of VO_{2max} in performance, considering that professional cyclists had a high value of this parameter and, for example, a three-week race is won by cyclists with high VO_{2max} (~85 ml·kg^{-1}·min^{-1}).

Maximal aerobic power (MAP) is the power output obtained at the VO_{2max} intensity. Likewise to VO_{2max}, MAP is a parameter that indicates the aerobic potential of athletes (13). There are several methods to establish MAP, both in laboratory and field conditions. The Graded Exercise Tests (GXT) is considered the gold-standard methodology for the determination of MAP. Typical increments in intensity range between 20 and 30 W with durations between 1 and 3 min (14). An example of a typical protocol with 25 $W \cdot min^{-1}$ increments is shown in Figure 3. However, the presence of different protocols in the scientific literature make the choice of selecting one or another difficult in their selection. These protocols have some limitations, for example, VO_{2max} and MAP values can fluctuate according to stage duration or power increments, (15, 16). Furthermore, the test is performed in laboratory conditions that are not "real" training or racing conditions.

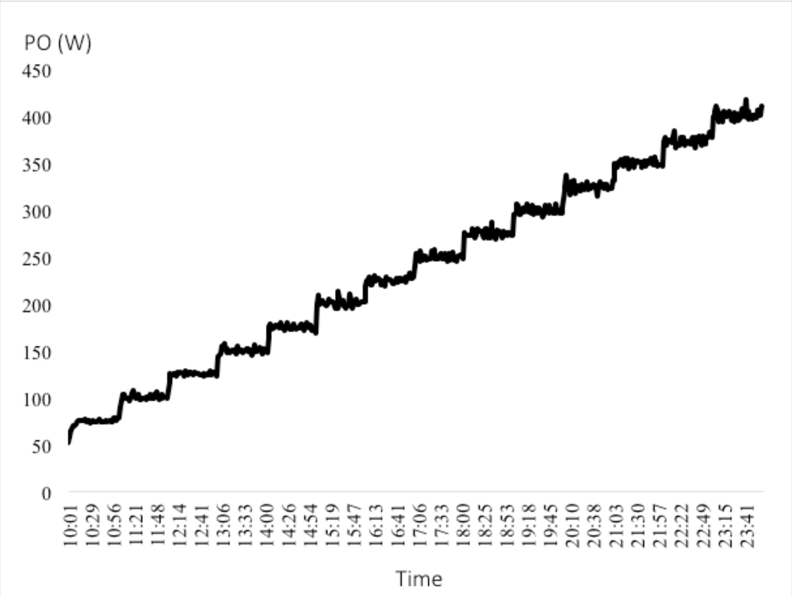


Figure 3. Power Output during a GXT

Pinot and Grappe (17) proposed a method to assess MAP in field conditions based on an individual's RPP. MAP is determined by modelling the aerobic metabolism from RPP with a linear PO-Log_t relationship between 5 min to 4 h (18). The first record power output included in a confident interval was taken as a MAP, and the sustained time of this power output was the time that this intensity can be sustained (17). This is a remarkable method to establish variables from the field because it does not require additional tests. Furthermore, it provides measures of power output taken directly from the field (training and racing) with a high level of accuracy.

Anaerobic threshold

Although MAP is an important parameter to predict performance in cyclists, when we talk about training, the boundary of sustainable performance seems more important than MAP mainly because this "threshold" has the highest correlation with performance and is more sensitive to performance changes during the training period (19, 20). This boundary is a dividing line between heavy and very heavy exercise, in other words, separating sustainable from unsustainable constant exercise. However, numerous physiological "thresholds" exist in the literature for exercise prescription and training load quantification, each of them with their own name and method for determination. In this section, we try to present the most reliable and easy methods to identify this point in power for training. Other highly reliable and accurate methods exist (i.e., Maximal Lactate Steady State [MLSS]), but nevertheless they require multiple sessions to assess it (16).

First, we talk about the anaerobic threshold which can be calculated with a respiratory exchange during GXT, and is considered the gold-standard method to identify this boundary (16). It is important to know that a variety of techniques for detecting this point exist, and can receive different names (i.e., lactate threshold, second ventilatory threshold, respiratory compensation point, etc.), but all of them refer to the same theoretical point. Anaerobic threshold occurs at the point in which lactate is rapidly increasing with intensity and represents hyperventilation relative to the extra CO_2 that is being produced. The biggest problem with these methods was the cost of GXT, which needed expensive devices and a specialist to analyse the ventilatory data.

In the case of having no access to a GXT with respiratory exchange analyse, other types of test can help to identify this "threshold" so important to training. With a similar incremental protocol like in GXT or an incremental cadence protocol against a constant load (21), it is possible to obtain a heart rate deflection point (HRDP). This method only requires a heart rate monitor to record the cyclist's HR during the incremental test. After that, with a simple visual (or more accurately, with a mathematical analysis) it is possible to identify the point in which the slope of the intensity-HR relationship decreased (Figure 4). However, the problem arises in cyclists without this HRDP. Many researchers have identified this point only in a portion of samples, as an example, Lucia, Hoyos

(22) reported the HRDP only in 56% of top-level cyclists and Jones and Doust (23) in 9 out of 15 well-trained male distance runners.

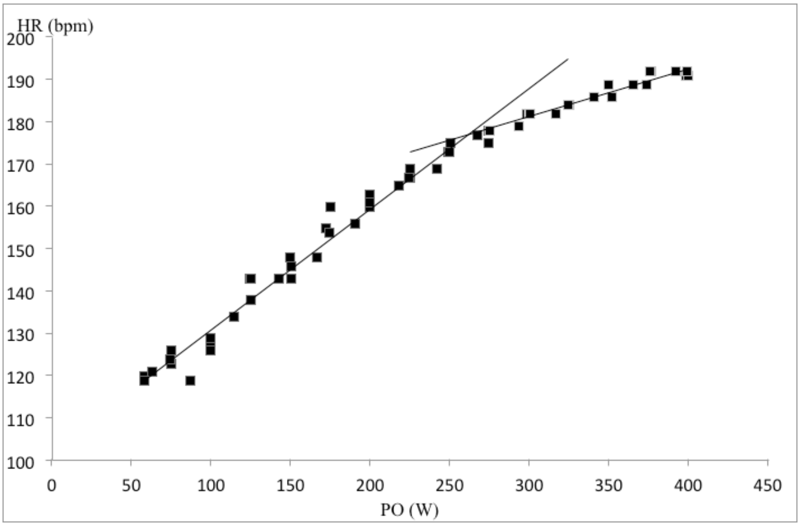


Figure 4. Detection of anaerobic threshold through the heart rate deflection point method (HRDP).

With the same mathematical or visual method and recent portable technology (i.e., Near Infrared Spectroscopy) it is possible to detect a deoxyhaemoglobin breakpoint in the evolution of this variable along the incremental test (24). This point is also related to anaerobic threshold (25). The popularity of Near Infrared is increasing among athletes because their size has been reduced, they have become wireless and they are becoming more accessible. In addition, these devices are compatible with most of the popular systems used to record training sessions, therefore making them easy to integrate for athletes.

Despite the reliability of these methodologies, all of them require complementary devices to assess anaerobic threshold and its associated power output. Because of that, methods which do not need more than a power meter are increasing their popularity. These methods are related to the 'critical power' concept which is defined as the asymptote of a curvilinear power-time relationship (Figure 5), in other words, it represents the power that can be theoretically maintained for a very long period (i.e., more than 30 min). Currently, there is controversy around this concept because some researchers have related this point with the anaerobic threshold while others indicate that they are close but are different boundaries (16). Nevertheless, as a practical application, Critical Power is being used satisfactorily as a point to differentiate heavy from very heavy exercise (24, 26). Concretely, the most used tests in the literature and in the field are the time-to-exhaustion trials (27) and a single 20 min time-trial (7, 28).

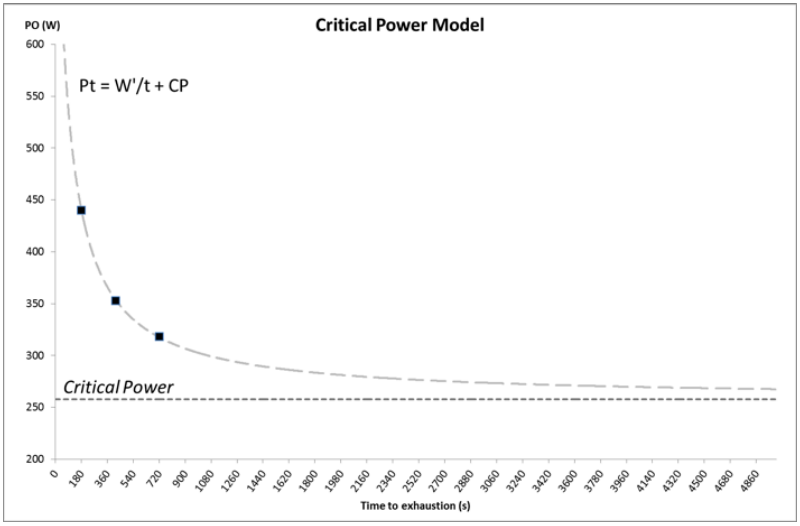


Figure 5. An example of the critical power model and their representation through three time-trials to exhaustion with different constant loads.

Regarding time-to-exhaustion trials for the determination of Critical Power, the cyclist needs to perform three to five constant-load trials to volitional exhaustion with a duration between 1 and 20 min (29), and a rest interval between each 30 min trial (20, 30). Mean power output of each trial will be used to perform a distribution for a curvilinear time-to-exhaustion relationship (Figure 5). Although this may sound very complicate to do, many of the software programs used to control the cycling training integrate the option to calculate the Critical Power indicating only the mean power output and duration of each trial. In single 20 min time-trials, also known as 'functional threshold power test', a term coined by Allen and Coggan (7), the mean power in this test was directly related to Critical Power and ventilatory threshold (20). Different recommendations are found between performing the test indoors or outdoors, and with or without a slope. Even though the previous multiple time-trial tests seem more reliable, a 20 min time-trial test is less fatiguing and easier to perform.

Practical applications and Conclusions

Road cycling is a sport with high metabolic demands in both, training and competition situations. Power meters have become one of the most used tools to measure the intensity of effort in professional cycling. Although there is a high amount of data available after finishing any recording, the analysis and interpretation of power output data allows a measure of the external load and could be used to track changes in fitness. The use of mean power output and normalized power combined with variability index allows a valid measure of the global impact or the training load. Furthermore, the RPP is a valid procedure to assess changes in fitness and performance and to establish intensity zones.

Aerobic performance plays a key role to achieve a good readiness-to-perform. Measuring VO_2max and anaerobic threshold and their derived power output variables allow the measurement of changes in fitness and performance. Although GXT is considered the gold standard to measure aerobic performance, field tests provide performance measures in "real" cycling conditions that could help cyclists and coaches without access to a laboratory to optimize training and establish performance.

References

1. Padilla S, Mujika I, Orbananos J, Santisteban J, Angulo F, Goiriena JJ. Exercise intensity and load during mass-start stage races in professional road cycling. Medicine and Science in Sports and Exercise. 2001;33(5):796-802.
2. Jobson SA, Passfield L, Atkinson G, Barton G, Scarf P. The analysis and utilization of cycling training data. Sports medicine. 2009;39(10):833-44.
3. Passfield L, Hopker JG, Jobson S, Friel D, Zabala M. Knowledge is power: Issues of measuring training and performance in cycling. Journal of Sports Sciences. 2016:1-9.
4. Mujika I, Padilla S. Physiological and performance characteristics of male professional road cyclists. Sports Medicine. 2001;31(7):479-87.
5. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. The Journal of physiology. 2008;586(1):35-44.
6. Sanders D, Myers T, Akubat I. Training Intensity Distribution in Road Cyclists: Objective Versus Subjective Measures. International journal of sports physiology and performance. 2017:1-20.
7. Allen H, Coggan A. Training and racing with a power meter: VeloPress; 2012.
8. Skiba PF. Evaluation of a Novel Training Metric in Trained Cyclists: 2415: Board# 94 June 1 2: 00 PM 3: 30 PM. Medicine & Science in Sports & Exercise. 2007;39(5):S448.
9. Mathiassen SE, Winkel J. Quantifying variation in physical load using exposure-vs-time data. Ergonomics. 1991;34(12):1455-68.
10. Abbiss CR, Straker L, Quod MJ, Martin DT, Laursen PB. Examining pacing profiles in elite female road cyclists using exposure variation analysis. British journal of sports medicine. 2010;44(6):437-42.

11. Pinot J, Grappe F. The record power profile to assess performance in elite cyclists. International journal of sports medicine. 2011;32(11):839-44.
12. Gonzalez-Alonso J, Calbet JA. Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. Circulation. 2003;107(6):824-30.
13. Pinot J, Grappe F. A six-year monitoring case study of a top-10 cycling Grand Tour finisher. J Sports Sci. 2015;33(9):907-14.
14. Pettitt RW, Clark IE, Ebner SM, Sedgeman DT, Murray SR. Gas exchange threshold and VO2max testing for athletes: an update. Journal of strength and conditioning research. 2013;27(2):549-55.
15. Hopkins WG, Schabort EJ, Hawley JA. Reliability of power in physical performance tests. Sports medicine (Auckland, NZ). 2001;31(3):211-34.
16. Pallares JG, Moran-Navarro R, Ortega JF, Fernandez-Elias VE, Mora-Rodriguez R. Validity and Reliability of Ventilatory and Blood Lactate Thresholds in Well-Trained Cyclists. PloS one. 2016;11(9):e0163389.
17. Pinot J, Grappe F. Determination of Maximal Aerobic Power from the Record Power Profile to improve cycling training. Journal of Science and Cycling. 2014;3(1):26.
18. Grappe F. Methods to assess performance in elite cyclists in the field. Aspetar Sports Medicine Journal. 2016;5:434-8.
19. Lucia A, Hoyos J, Perez M, Santalla A, Earnest CP, Chicharro JL. Which laboratory variable is related with time trial performance time in the Tour de France? British journal of sports medicine. 2004;38(5):636-40.
20. Nimmerichter A, Williams C, Bachl N, Eston R. Evaluation of a field test to assess performance in elite cyclists. International journal of sports medicine. 2010;31(3):160-6.
21. Grazzi G, Mazzoni G, Casoni I, Uliari S, Collini G, Heide L, et al. Identification of a Vo2 deflection point coinciding with the heart rate deflection point and ventilatory threshold in cycling. Journal of strength and conditioning research. 2008;22(4):1116-23.
22. Lucia A, Hoyos J, Santalla A, Perez M, Carvajal A, Chicharro JL. Lactic acidosis, potassium, and the heart rate deflection point in professional road cyclists. British journal of sports medicine. 2002;36(2):113-7.
23. Jones AM, Doust JH. Lack of reliability in Conconi's heart rate deflection point. International journal of sports medicine. 1995;16(8):541-4.
24. Keir DA, Fontana FY, Robertson TC, Murias JM, Paterson DH, Kowalchuk JM, et al. Exercise Intensity Thresholds: Identifying the Boundaries of Sustainable Performance. Med Sci Sports Exerc. 2015;47(9):1932-40.
25. Bellotti C, Calabria E, Capelli C, Pogliaghi S. Determination of maximal lactate steady state in healthy adults: can NIRS help? Med Sci Sports Exerc. 2013;45(6):1208-16.
26. Rossiter HB. Exercise: Kinetic considerations for gas exchange. Comprehensive Physiology. 2011;1(1):203-44.
27. Karsten B, Jobson SA, Hopker J, Stevens L, Beedie C. Validity and reliability of critical power field testing. European Journal of Applied Physiology. 2015;115(1):197-204.
28. Bentley DJ, McNaughton LR, Thompson D, Vleck VE, Batterham AM. Peak power output, the lactate threshold, and time trial performance in cy-

clists. Med Sci Sports Exerc. 2001;33(12):2077-81.
29. Morton RH. A 3-parameter critical power model. Ergonomics. 1996;39(4):611-9.
30. Galbraith A, Hopker J, Lelliott S, Diddams L, Passfield L. A single-visit field test of critical speed. International journal of sports physiology and performance. 2014;9(6):931-5.

Characteristics of open water lifesaving

J. Arturo Abraldes[1,2] and Ricardo J. Fernandes[3,4]

Introduction

Lifesaving sport contains many disciplines that take place in swimming pool and open water. All these disciplines are born from the imitation of the rescues that lifeguards undertake while on duty in inland and/or open water environments. However, lifesavers reproduce the rescue sequences and demonstrate the domain of specific rescue materials not aiming to save the "victim" but to act in the fastest possible way (1,2). This characteristic of speed makes the sport interesting, challenging and exciting (3,4), but while in some countries it is popular (e.g. Spain and Australia), in some others it is unknown or not interesting to be exercised. This is the case even in other geographic areas close to rivers, lakes and seas.

Lifesaving in Europe is operated by the International Life Saving Federation of Europe (5), a member of the International Life Saving Federation (6). Its main institutional responsibility is the promotion and diffusion of water safety throughout the world. The regular participation in national and international competitive events promotes higher lifesaving experience and knowledge, particularly of its training process, structure and organization. This know-how is fundamental and allows the sport to develop its bases, to be established and spread. In addition, it assists its promotion at local level and to obtain a greater awareness and education allowing reducing the number of drowning accidents (7,8).

We consider very important to disseminate and reinforce the existing knowledge on lifesaving to promote it and increase the number of practitioners. Lifesaving is complex, with a relationship between the aquatic displacement techniques and the use of specific materials, allowing a greater control of the shore and aquatic environments. Complementarily, preventive habits instilled with its practice are as (or more) important

1 Faculty of Sport Sciences, University of Murcia, Spain
2 Lifesaving Federation of Galicia, Spain
3 Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal
4 Porto Biomechanics Laboratory, University of Porto, Porto, Portugal

as the rescue techniques, leading to the prevention of accidents and to a reduction in the number of rescues (4). In this sense, in addition to the sportive instruction of the practitioner, lifesaving aims enhancing the integral education of the individual, particularly regarding the respect and understanding of the dangers that exist in each aquatic environment.

Further to previously published work (e.g. 9,10), the aims of this chapter are: (i) to disclose lifesaving as a regulated sport with a specific competitive calendar; (ii) to identify the specific characteristics of the different lifesaving events carried out in natural spaces (at the beach); (iii) to propose a proper teaching model for the advancement of learning and the improvement of the sport techniques; and (iv) to summarize the latest findings of scholarly work that has been undertaken about lifesaving.

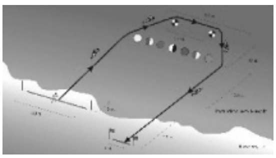
Development

Competitive lifesaving can take place at the swimming pool or on the beach, presenting diverse individual and team events in the juvenile (15-16 years), junior (17-18 years) and absolute (over 15 years) age groups (11). In addition, contrary to what many people might think that only professional lifeguards and / or adults are engaged in competition, there are also competitive events for younger individuals (just above seven years of age). These events for younger age groups have adapted distances, materials and technical elements (as described in Table 1).

Table 1. Lifesaving open water competitive events by age group.								
Age groups (years old):	7-8	9-10	11-2	13-4	15-6	17-8	>15	>30
Individual events								
Surf race	·	·	·	·	·	·	·	·
Board race	·	·	·	·	·	·	·	·
Surf ski race					·	·	·	·
Beach flags	·	·	·	·	·	·	·	·
Beach sprint				·	·	·	·	
Run–swim–run					·	·	·	
Ocean man/woman					·	·	·	
Team events								
Board rescue			·	·	·	·	·	·
Rescue tube rescue			·	·	·	·	·	·
Beach run relay	·	·	·	·	·	·	·	
Ocean man/woman relay					·	·	·	
Ocean man mixed					·	·	·	

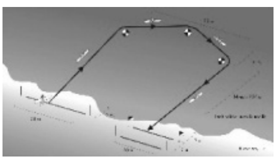
For a better understanding of this sport, there is a need to know the characteristics of the different competitive events (i.e., the disciplines), namely understanding its general rules (in which the events are described) and the specific organization procedures of each championship (e.g. how many series are there, how many swimmers can access the finals and how many points the winner can obtain). So, in Tables 2 and 3, it is described the standard international individual and team events for youth, junior and absolute age groups, highlighting the details that influence the final competitive outcomes (1,11-13).

Table 2. Brief description of the lifesaving all age-groups individual events carried out on natural spaces (adapted from 3,7).



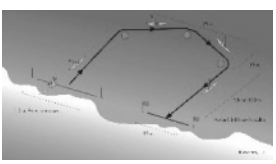
Surf race

After the auditory signal, lifesavers enter the water, swim around the buoys clockwise, return to shore and end their path between the two green flags.



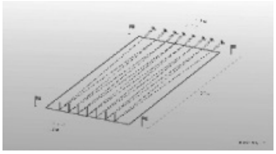
Board race

With three buoys in triangular position indicating the route, the lifesavers enter the water after the starting signal, paddling with the hands their board. They surpass the buoys clockwise, until arriving at the finish line in contact with the board.



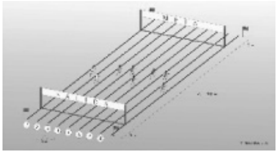
Surf ski race

Three buoys in triangular position indicate the path that the lifesavers must follow. They are in-water holding the boat and, after the exit signal, rise and move on it, passing the buoys clockwise. They must cross the finish line on the boat.



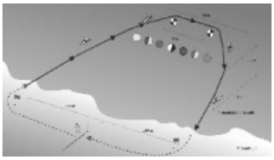
Beach flags

Lifesavers are in lying prone position and some flags are placed 20 m apart (one less that the number of competitors). After the exit signal, each swimmer lifesaver tries to catch a flag located behind him. Those that do not get it are eliminated.



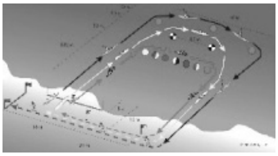
Beach sprint

The competition area is marked in 70-90 m lanes separated by coloured ropes. After the auditory signal, lifesavers must run in straight-line, barefoot and without help of any artificial material towards the finish line.



Run–swim–run

From the start line, competitors run 200 m, surround the flag and enter the water swimming around the buoys. Then, they return to the beach, turn on the flag and run 200 m towards the finish line.

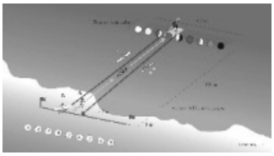


Ocean man/woman

After the exit signal, swimmers' lifesavers carry out the specified trajectories for the surf, board race and surf ski race events, finishing running on the sand until the finish line. The order of the segments is draw and decided beforehand.

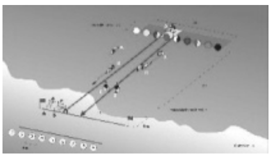
In team competitions, in addition to individual efficiency, close attention should be given to the coordination and collaboration between team members, which will significantly affect the event outcome.

Table 3. Brief description of the lifesaving all age-groups team events carried out on natural spaces (adapted from 3,7).



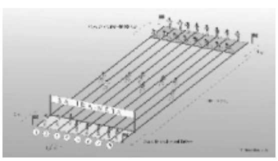
Board rescue

At the starting signal, the first competitor swims until the corresponding buoy, indicating its arrival touching it with one hand and raising the other. His team-mate enters the water with the lifeline and approaches the colleague that will rise to the board and collaborate on the way back.



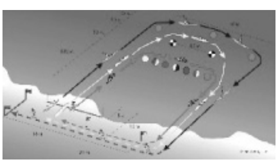
Rescue tube rescue

With four participants, at the starting signal, the first one swim until its corresponding buoy and raises one upper limb. The second one swim with fins and a rescue tube to the buoy attaching it to the colleague and towing him to shore. The other two lifesavers can assist in the extraction until the finish line.



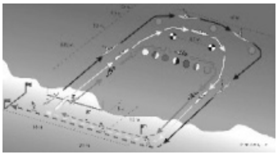
Beach run relay

With four barefoot participants in each team, the first competitor at the end of his run gives the baton to the second, who must be in the changeover zone. He shall deliver the baton to the third and this one to the fourth, who will finish the event by passing the finish line.



Ocean man/woman relay

Each of the four participants will make a leg (surf, board race and ski surf race, by the order established in the draw) after being touched by the incoming team-mate. The fourth lifesaver ends the relay with a sprint on the beach until the finish line.



Ocean mixed

A path equivalent to two ocean man/woman races will be made by a team of three male and three female lifesavers. Each participant will take a leg after being touched by the previous and the last participant will end the relay with a sprint on the beach until the finish line.

Lifesaving classification

Of the various possible classifications for this sport, we use the one that considers the motor situations as systems whose components interrelate and generate a certain degree of uncertainty in the participants (14). This classification was previously used by others (see 15-17) and is based on the following assumptions (Figure 1): (i) "C" refers to the existence of teammates and, consequently, to the need for motor collaboration relationships; (ii) "A" refers to the existence of adversaries and the relationship of motor opposition; and (iii) "I" refers to the fact that the environment where the sport occurs offers uncertainty, i.e., if the sport context provides relevant information that implies adaptation by the practitioner or if it is closed and normalized.

The three above mentioned criteria, combined binary and underlined (just in case that one, two or three elements are absent), lead to the establishment of eight distinct categories arranged in tree shape, in which lifesaving is situated (18). Thus, depending on the presence/absence of one, two or three of these elements, it will be defined the category in which the sport in question is placed (when one of the three elements is missing, the corresponding letter is highlighted; Figure 1). After observing the general social and psychomotor characteristics of lifesaving, and understanding the motor actions of each, it will be possible to dispose of a rigorous base to propose motor games, exercises and/or tasks that fit each group of events and what they require.

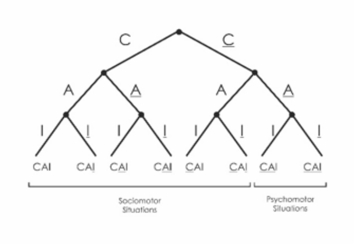


Figure 1. Tree diagram representing the eight categories and corresponding classification criteria of sport events (adapted from 18).

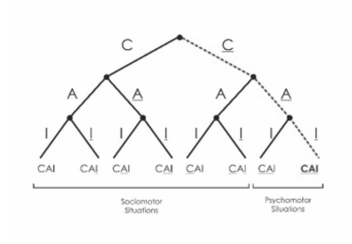


Figure 2. Representation of the beach sprint event in lifesaving (adapted from 17)

According to the above-mentioned criteria, only the beach sprint event would have the psychomotor profile (Figure 2), in which the relationship with the other lifesavers is not relevant. This is a typical case of a psychological non-motor interaction, in which the opponent does not interfere with (or influence) the motor actions of the other participants. Here, there are situations of co-motricity, existing an action in the presence of others but without a body or instrumental interaction (18), allowing the lifesaver to see the actions of his opponent that can serve as an emotional stimulus. In these events there are not colleagues and opponents within a stable physical environment and, because they cannot leave their respective lanes where exercise is performed, each competitor does not have the collaboration of teammate(s), nor opposition, hindering or interactions of opponents.

No doubt that the beach flags event is more complex from a strategic point of view, since members of the same team can compete in the same race. Therefore, “CAI” gives a new classification of lifesaving (Figure 3), making essential the collaboration with peers and the clear interaction with opponents (occurring in a stable and non-changeable environment). The existence of interactions with colleagues requires a well-established preparation of the event, since there will be moments that one, two or three lifesavers of the same club are running simultaneously and should cooperate to obtain benefits to the team. This is, without a doubt, an event with multiple strategic possibilities (that can be established before and during the race). According to the lifesaving rules, the competitor cannot grasp or push the opponents, but it is possible to use the body positioning before the flag collection, which makes evident the “opposition” nature of the event.

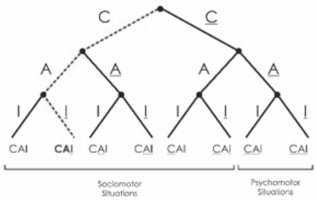


Figure 3. Representation of the beach flags event (adapted from 17).

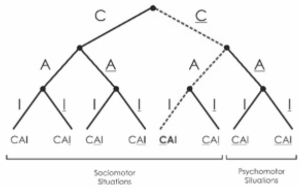


Figure 4. Representation of the other individual events (adapted 17).

When other open water individual events (surf race, boar race, surf ski race, run-swim-run and ocean man/woman) are analysed, it is observed no essential communicative interaction, i.e., there is no collaboration (although the presence of adversaries that can influence the course of the event; cf. Figure 4). It is also evident the high uncertainty of the sea, plagued by currents and waves (depending on the place on the event occurs) determining the lifesavers' actions. The improbability of the sea requires a large environment deciphering because, although it is not a completely unknown environment as it is partially signalised (e.g. as a river descent), the lifesaver needs to interpret the signals and adapts his motor actions. In fact, despite being partially signalized, there are no lanes delimiting the right course, evidencing its socio-motor characteristics. All these imply that participants make their decisions depending on the environment and the opponents, having automatized their cyclic propelling movements (with or without materials) but, simultaneously, needing to adapt to the opponents' actions.

All team events present the tree exponential branch (Figure 1) that ends within the socio-motor situations, even if they occur in a space divided by lanes and without opponents' relevant interactions (e.g. beach run relay). In this event, "CAI" shows a cooperative type interaction with other participants, namely during the moment of the touch when giving the baton (Figure 5), i.e., it requires evident cooperation in-between team components. Despite being conducted in open water and on the sand, this is a closed event since the paths are specifically delimited and the competitive space is well established. Without a doubt, it is a rather disputed competition, with more emphasis on the physical conditioning than on tactics.

The board rescue, rescue tube rescue, ocean man/woman and ocean mixed events are much more complex, with interactions with peers and opponents, within an unstable environment such as the sea (Figure 6). These “ingredients” evidences their high complexity, with actions of all kinds and well-coordinated cooperation, where team training is decisive. They are highly complex events in terms of motricity, i.e., competitions in which lifesavers should decipher the opponent actions that might have strategic significance, need to interpret the sea fluctuating information, as well as to adapt themselves to the other participants’ actions.

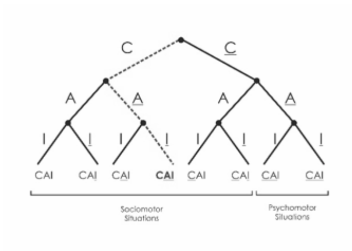


Figure 5. Representation of the beach run relay event (adapted from 17).

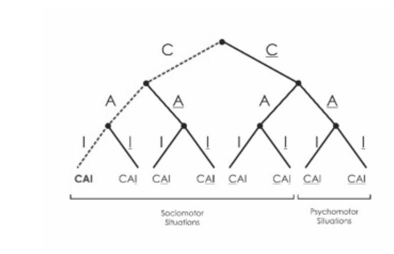


Figure 6. Representation of the other team events (adapted from 17).

The different lifesaving events present five different branches in the exponential tree diagram, indicating a great motor and situational complexity. In that diagram it is possible to observe that four “CAI” groups of events end in socio-motor situations. Thus, lifesaving is considered a sport of great socio-motor character, contrary to what common sense could tell. The fundamental motor actions technical aspect in all events (which would not agree with the greater tactical aspect of the socio-motor practices in general) should not be considered an error, but as the consequence of the variety of its fundamental characteristics, a very rare feature in most sports. Therefore, lifesavers must master those aspects that relate to psychomotor situations, with characteristics such as (18): (i) a tendency to motor stereotype; (ii) a pre-programed behaviour and anticipation; (iii) predominantly proprioceptive regulation; (iv) omission of motor decoding; (v) intense training; and (vi) competitive results. However, the large number of branches and socio-motor events in which it could be found performance relevant aspects should not be unconsidered, such as: (i) the high importance of the prior strategy and strategic decision of the player and (ii) the training of key moments at the time of collaborate with colleagues effectively.

Analysis of sports initiation and high-performance participation

Sport initiation begins when the individual has a basic and general enrolment with the overall set of activities, being included on a learning process aiming to acquiring a practical (and conceptual) contents domain (19-21). This teaching process is of special importance to the learning success and contrasts with the typical focus on the result that coaches usually privilege.

A detailed analysis of sport initiation specifically focusing on lifesaving is already available (cf. 1,3,9), in which the topics sport initiation, training context, reasons for selecting this sport and the context in which the lifesaver is inserted are well described. The analysis of these items shows similar data for the two lifesaving modalities (swimming pool and open water events), particularly regarding the fact that lifesavers engage in this sport at the age of 12 (with a decrease tendency in the last years due to the growing number of participants in lower age-groups; 15).

Participants usually begin their competitive participation in swimming pool conditions rather than in open water events, with conventional swimming skills as the basis for the posterior development of specific rescue techniques. In the most cases, lifesavers keep practicing two sports (lifesaving and swimming) during the training season, with their training processes improving in quality with the increasing number of coaches with higher education in sports science, as well as with better quality specific material resources. The fact that they train, at least, four to five workouts per week, combining water and dry land exercises, is leading to significant performances improvement with numerous records in the last decade.

The main motivation for lifesaving practice is intrinsic, mainly supported in the enjoyment for the activity (22). This leads to a strong engagement on the sport since the lifesavers that have initiated practice in yearly ages are still involved and competing in absolute or masters categories. This is also reinforced by extrinsic factors, particularly by the pleasure to achieve success in an ample number of events and competitions, and by the environment around the lifesaver. In fact, family and coaches are the lifesavers main supporters (23) as their parents are also engaged in sport practice (in general) and coaches are also involved with lifesaving practice.

Analysis of technical elements

In the following points it will be described, in the order that they are used in competition, the technical elements included in open water lifesaving events (1,2,7,24): (i) running, which relates to the different displacements of the lifesaver along the beach soft or hard sands (drier and wetter, respectively) to reach the water or as a part of the event (e.g. beach flags, beach run relay or run-swim-run); (ii) water entry, which reflects to the moment of water entering in contact with the material later used during the event or without it (in those events that material is not needed); (iii) swimming approach, i.e., the propelling techniques for moving in-water between the points previously defined, depending directly on the event characteristics, specific rules and lifesavers physical conditioning; (iv) swimming approach with and aid, regarding to the lifesaver in-water movement mounted on a specific material (according to the event rules), never loading or pulling it; (v) placing material, referring to the placement of different material by the lifesaver to itself during the event (not beforehand);

Other open water lifesaving events technical elements are: (vi) placing material to the "victim", related to the placement of different material by the lifesaver to a "drowning" partner (according to the event rules) that will later be used to tow and continue or end the event (the "victim" can grab the rescue aid and assist in the towing); (vii) towing, referring to the transportation of a colleague through the water, always with the airways above the surface so the "victim" can breathe (the direct towing is done with body to body contact and without material, with the indirect technique requiring the use of material); (viii) moving on the material, by transporting the "victim" on lifesaving specific material, who can help with upper and/or lower limbs actions to make the course as fast as possible; (ix) visual signalling, i.e., visually perceiving a specific teammate gesture authorizing the beginning of the following lifesaver action; (x) coordination with the partner, referring to the collaboration of two or more lifesavers of the same team with the intention of correctly executing different event actions aiming for a better final result; and (xi) water extraction, related to one or more lifesavers action when extracting a "victim" from the water to a firm and safe place (the beach sand).

Some technical elements are used in most of the events (evidencing its importance), while others only in one (with lower transference to the professional lifeguards' activities; Table 5). To begin practicing this sport, a great variety of technical aspects should be taught. In fact, even if not performed perfectly, it is very important to have a substantive variety of actions, leading to a future better control of the overall lifesaving techniques.

Table 5. Motor actions present in open water lifesaving events (adapted from 7).

Events	Surf race	Board race	Surf ski race	Beach flags	Beach sprint	Run-swim-run	Ocean	Board rescue	Rescue tube rescue	Beach run relay	Ocean relay	Ocean mixed
Running	·	·		·	·	·	·	·	·	·	·	·
Water entry	·					·	·	·	·		·	·
Water entry with material		·					·	·	·		·	·
Swimming approach	·					·	·	·	·		·	·
Swim approach material		·	·				·	·			·	·
Placing material on itself									·			
Placing material on victim									·			
Towing (indirect)									·			
Moving on the material								·			·	·
Visual signalling									·		·	·
Coordination with partner									·	·	·	·
Water extraction									·			

In addition, the use of materials in the different lifesaving events evidences a high complexity comparatively, for example, to conventional swimming (Table 6). This forces the lifesaver to dominate specific material, overcoming him aiming for greater performance effectiveness.

Table 6. Materials used in open water lifesaving events (adapted from 7).

Events	Surf race	Board race	Surf ski race	Beach flags	Beach sprint	Run-swim-run	Ocean	Board rescue	Rescue tube rescue	Beach run relay	Ocean relay	Ocean mixed
Fins									·			
Rescue tube									·			
Rescue board		·					·	·			·	·
Ski			·				·				·	·
Baton				·						·		
Signalling ropes				·	·					·		
Signalling flags	·	·	·			·	·	·	·		·	·
Signalling buoys	·	·	·			·	·	·	·		·	·

Some specific materials differ accordingly to the distinct competitive levels, while others have the same characteristics regardless the age groups in competition. For example, the rule regarding fins area allows a maximum of 30 x 65 cm in width and length for all categories, but these dimensions imply a greater effort for the young lifesavers comparing to adults, influencing their normal physical development (24). This is the reason why some authors propose some material adaptations for the younger age categories, like the use of smaller fins (24,25), respecting their growing and maturation process.

Bioenergetical analysis

Open water lifesaving events do not have any defined standard times or records since the sea, sand and wind conditions are extremely variable. Moreover, there is a mix of exercise modes in some events (e.g. running, swimming and towing) and others include significant exercise rhythm changes. Thus, it is very hard to well define which are the main energy systems supporting the different lifesaving events. In addition, the environmental conditions turn very hard the use of laboratorial instrumentation, not allowing the variables that are typically used to asses aerobic and anaerobic energy contributions, as the oxygen uptake and blood lactate concentrations to be measured well (cf. 26). There are some pioneering studies attempting to classify some parts of lifesaving sport events based on their bioenergetical demands (e.g. 27), but they suffer serious limitations or are insufficient, and thus they do not describe the total course of the event.

Notwithstanding these limitations, it is possible to state that, due to evident duration variability of the lifesaving events (from few seconds to several minutes), all the energy pathways are relevant for lifesaving. However, in the short-term future, the bioenergetical characterization of each event should be done to observe the aerobic and anaerobic (lactic and alactic) contributions. Following the literature (28-31) we hypothesized that: (i) the ATP-CP contribution during short and explosive courses lasting between ~5 - 15 s (e.g. beach flags and sprint events) will be the most determinant; (ii) the anaerobic energy from the glycolysis would be fundamental in events lasting between 1 - 2 min (e.g. board rescue and rescue with tube rescue); (iii) the maximal oxygen uptake would significantly determine performance on events taking about 4 - 8 min to end (e.g. surf and board races); and (iv) the anaerobic threshold (the gold standard indicator of the aerobic capacity development) would be fundamental at events of 20 - 40 min duration (as the ocean man/woman).

As the energy for the lifesavers muscular work comes from both aerobic and anaerobic sources, it is important to emphasize that their training process should, mainly during the specific preparation stage of the preparatory period and the competitive period, focus on the bioenergetical zones that mimic those requested in competition. Considering most of the durations in the various lifesaving events, it seems obvious that the importance of the aerobic component, although never negligible (cf. 32), should be secondarily related to the development of the anaerobic energetic pathway (both in its lactic and ATP-CP components).

Thus, the development of the anaerobic (or glycolytic) power and anaerobic capacity (also known as lactic tolerance) implies the development of (33): (i) the enzymatic activity responsible for the degradation of glycogen to lactic acid and (ii) the muscular capacity to continue exercising in adverse physiological and cellular environments (due to metabolic acidosis), and the increase in muscle reserves of glycogen. Other training areas should also be developed, namely those that are adjacent to those mentioned above, particularly the aerobic power (aiming developing oxidative energy processing for muscular work) and speed (aiming potentiating the phosphagen use and the neuromotor domain). Training exercises focusing on aerobic capacity development, both for raising the exercise intensity corresponding to the anaerobic threshold, as well as to increase the effectiveness of the recovery process, should also be implemented but mainly at lower ages and sports levels, as well as at the general preparation stage of the preparatory period.

The lifesavers biotype

Several studies indicate the existence of different physical biotypes regarding the type of exercise performed (e.g. 34) and, even, the specific position per sport (35,36). This kind of easy-to-conduct studies is essential to better know the body characteristics of the participants, and even to detect sports talents in the initial stages of practice. Obviously, lifesaving characteristics imply a specific biotype in accordance with the competitive requirements. The first study in this field, although using a rather heterogeneous sample and including subjects engaged in unsystematic training process, indicated that lifesavers have a high percentage of body fat and, therefore, a lower percentage of lean mass (37). Subsequently, it was verified that the meso-endomorphy was the predominant somatotype category in all lifesaving competitive age groups (38-40).

A more recent study analysed lifesavers according to their competitive specialty and verified the existence of balanced mesomorph and meso-endomorphic somatotypes for men and women swimming pool experts, respectively (41). It also observed relevant anthropometric differences between open water and swimming pool specialists. More precisely, it was found that: (i) open water females are leaner and have lower bi-acromial and bi-iliocrystal perimeters; and (ii) open water males display lower weight, height, body mass and percentage of muscle mass, which may be more adequate to the techniques used when moving on the board and ski. However, most studies highlight the lifesavers low level of specialization, indicating that their main differences are related to strength related parameters (42). Figure 7 shows the somatotypes for male and females lifesavers.

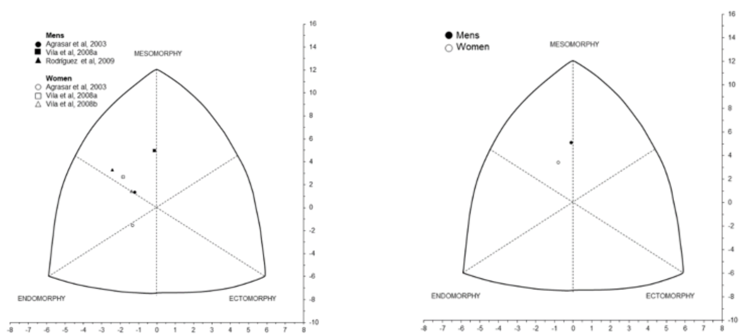


Figure 7. Somatochart representing lifesavers somatotypes as it is described in the specialized literature: male vs female lifesavers in lifesaving events in general and only for open water events (left and right panels, respectively).

Conclusion

The long-time duration of the training process (no matter the sport analysed) and the high level of competences it requires, determine that coaches should well-know how to focus on the essentials of sportive preparation. Speaking about sports in general, and in lifesaving, this should be done by responding directly to each lifesaver needs and in the most incisive, pragmatic and consequent way possible. We hope that this text can help those involved in the sport promoting the evolution of lifesavers both in quantitative terms (augmenting the number of people engaged on its practice), as well as regarding the quality of the future results.

References

(1) Abraldes JA. Salvamento Acuático Deportivo. Un deporte solidario. La Coruña: Xaniño Editorial. 2004.
(2) Pascual LF. Salvamento Acuático Profesional en piscinas y su relación con el salvamento acuático deportivo en aguas cerradas. Tesis doctoral no publicada, Universidad de Zaragoza; 2004.
(3) Abraldes JA. Formación deportiva en Salvamento Acuático. Investigación en el Campeonato de España de Autonomías. La Coruña: Federación de Salvamento e Socorrismo de Galicia. 2009.
(4) Pelayo P, Cocu PC. Natation: le sauvetage. EPS, Revue Education Physique et Sport, 1992; 236: 21-23.
(5) International Life Saving Federation of Europe. The official website of the International Life Saving Federation of Europe. 2017 [cited 2017 oct 3]; Available from: http://europe.ilsf.org/.
(6) International Life Saving Federation. The official website of the International Life Saving Federation. 2017 [cited 2017 oct 3]; Available from: http://www.ilsf.org.
(7) Abraldes JA. Salvamento acuático y deporte: Un estudio de los recursos humanos en las playas de Galicia, intervención en los rescates y su relación con el ámbito deportivo. Coruña: Federación de Salvamento e Socorrismo de Galicia. 2008.
(8) Paredes T. El deporte en el Salvamento Acuático. Barcelona: Federación Española de Salvamento y Socorrismo. Documentación no publicada; 1991.
(9) Abraldes JÁ, Fernandes RJ. Salvamento desportivo em piscina: caracterização, iniciação desportiva, treino e investigação. In: Morouço P, Batalha N, Fernandes RJ editors. Natação e Atividades Aquáticas: Pedagogia, Treino e Investigação, Escola Superior de Educação e Ciências Sociais, Instituto Politécnico de Leiria, Leiria. 2016. p. 220-242.
(10) Avramidis S, Abraldes JA, Hodgetts D. Modern Scientific Approaches of Lifesaving Sport. In: Avramidis S editor. Lifesaving Sport. History, Competition Rules, Fair Play, Special Issues Athens, Greece: Stamoulis Publishing; 2017. p.391-403.
(11) International Life Saving Federation. Competition rule book. Rules, Standards and Procedures for Lifesaving World Championships and ILS-sanctioned Competitions. 2015-2019 Edition. Leuve, Belgium: Author; 2015.
(12) Abraldes JA. Fundamentos del Salvamento Acuático Deportivo. Murcia: Universidad de Murcia y Open Coruseware; 2011 [cited 2017 Sept 30] Available from: http://ocw.um.es/cc.-sociales/fundamentos-del-salvamento-acuatico-deportivo.
(13) Real Federación Española de Salvamento y Socorrismo. Reglamento de competición. 2015-2016. Madrid: Real Federación Española de Salvamento y Socorrismo; 2015.
(14) Portí G. Las modalidades de escalada. VI Seminario Internacional de praxiología motriz. Madrid; 2001.
(15) Parlebas P. Elementos de sociología del deporte. Málaga: Unisport; 1988.
(16) Alonso JI, Abraldes JA. Análisis y clasificación del salvamento acuático deportivo desde su estructura y su dinámica. In: Palacios P et al. editors. 3er

Congreso de Salvamento y Socorrismo de Galicia. La Coruña: Fundación IDISSA; 2003. p.303-21.
(17) Alonso JI, Abraldes JA. Análisis de las situaciones motrices lúdicas en el salvamento acuático deportivo. In: Abraldes JA, Rodríguez N editors. El salvamento acuático deportivo a estudio. La Coruña: Federación de Salvamento e Socorrismo de Galicia; 2007. p.183-208.
(18) Parlebas P. Juegos, deporte y sociedad. Léxico de Praxiología Motriz. Barcelona: Ed. Paidotribo; 2001.
(19) Blázquez D. La iniciación deportiva y el deporte escolar. Barcelona: INDE. 1995.
(20) Hernández-Moreno J. Baloncesto: Iniciación y entrenamiento. Barcelona: Paidotribo; 1988.
(21) Sánchez-Bañuelos F. Bases para una didáctica de la Educación Física y el deporte. Madrid: Gymnos; 1984.
(22) Granero-Gallegos A, Gómez-López M, Rodríguez-Suárez N, Abraldes JA. Analysis of motivational aspects in lifesaving sport. FEGUI, Revista de Salvamento Acuático y Primeros Auxilios, 2012; 36(4), Supl. 1: 80-81.
(23) Dosil J. Psicología de la actividad física y del deporte. Madrid: McGraw-Hill; 2004.
(24) Abraldes JA, Rodríguez N. Posibles adaptaciones das pruebas realizadas en aguas abiertas y desarrolladas por las categorías alevín, infantil y cadete. I Congreso Congrés Català de Salvament Aquàtic. Barcelona. 2002 nov.
(25) Del Castill M, Abraldes JA. Estudio del salvamento acuático deportivo en la categoría alevín. In: IV Jornadas Técnico-Profesionales de Salvamento Acuático, Segovia; 2000.
(26) Figueiredo P, Zamparo P, Sousa A, Vilas-Boas JP, Fernandes RJ. An energy balance of the 200 m front crawl race. European Journal of Applied Physiology, 2011; 111: 767-77.
(27) Sousa A, Fernandes RJ, Rodríguez N, Abraldes JÁ. Influence of a 100 m simulated in-water rescue on cardiopulmonary parameters. Prehospital Emergency Care. 2017; 21(3): 301-308.
(28) Abraldes JA, Rodríguez N, Editors. El salvamento acuático deportivo a estudio. La Coruña: Federación de Salvamento e Socorrismo de Galicia; 2007.
(29) Calvo J. Aproximación al salvamento acuático en las categorías infantil y cadete. In: Abraldes JA, Rodríguez N editors. El salvamento acuático deportivo a estudio. La Coruña: Federación de Salvamento y Socorrismo de Galicia; 2007. p. 61-112.
(30) Ferragut C, Vila H, Rodríguez N. Aspectos fisiológicos a tnere en cuenta en el salvamento acuático deportivo. In: Abraldes JA, Rodríguez N editors. El salvamento acuático deportivo a estudio. La Coruña: Federación de Salvamento e Socorrismo de Galicia. 2007. p.161-82.
(31) Heredia, JM., Aparicio, VA. y López, M. Evaluación y cuantificación de las cargas de entrenamiento e de los deportistas de salvamento y socorrismo mediante el uso de tecnología GPS. In: Abraldes JA y Rodríguez N editors. Estudios en torno a una necesidad: Salvamento y Socorrismo Acuático. La Coruña: Federación de Salvamento e Socorrismo de Galicia, 2008, p. 109-117.
(32) Gastin PB. Energy system interaction and relative contribution during max-

imal exercise. Sports Medicine, 2001; 31(10): 725-41.
(33) Olbrecht J. The Science of winning: planning, periodizing and optimizing swim training. Luton: Swimshop; 2000.
(34) Malina RM, Bouchard C, Bard-Or O. Growth, maturation and physical activity. Illinois: Human Kinetics; 2004.
(35) Sands WA, Smith LS, Kivi DM, McNeal JR, Dorman JC, Stone MH. Anthropometric and physical abilities profiles: US National Skeleton Team. Sport Biomechics, 2005; 4(2):197-214.
(36) Canossa S, Abraldes JA, Soares S, Vila MH, Ferragut C, Rodríguez N, Argudo FM, Fernandes RF, Garganta JM. Contrasting morphology and training background in waterpolo teams of different competitive levels. Motriz. Journal of Physical Education, 2014; 3:272-79.
(37) Agrasar C, Abraldes JA, Rodríguez N, Villar JM. Estudio cineantropométrico, de la composición corporal y el somatotipo dos componentes de la selección gallega de salvamento acuático deportivo. In: Palacios P et al. editors. 3er Congreso de Salvamento y Socorrismo de Galicia. La Coruña: Fundación IDISSA; 2003. p.263-69.
(38) Ferragut C, Rodríguez N, Vila H, Alacid F, Abraldes JA. Study of the biotype and the body composition of the gallega male in lifesaving. In: Abraldes JA, Rodríguez N editors. Book of abstracts International Lifesaving Congress 2007. La Coruña: Lifesaving Federation of Galicia; 2007. p.77-78.
(39) Rodríguez N, Vila MH, Ferragut C, Abraldes JA. Perfil antropométrico dos deportistas infantiles de salvamento acuático deportivo. In: Martínez MJ, García JL, Arufe V editors. III Congreso Nacional de Ciencias del Deporte. Barcelona: ACUGA y Alto Rendimiento; 2007. p.1-9.
(40) Rodríguez N, Abraldes JA, Ferragut C, Vila H. Salvamento acuático deportivo. Un estudio de la población masculina de Galicia. In: Arufe V, García JL, Lera A editors. V Congreso Nacional de Ciencias del Deporte y Educación Física. Pontevedra: Alto Rendimiento; 2009. p.1-10.
(41) Abraldes JA, Rodríguez N, Ferragut F, Vila MH. Características antropométricas, composición corporal y somatotipo en deportistas de élite de salvamento. RETOS. Nuevas tendencias en Educación Física, Deporte y Recreación. 2014; 26(2), 66-70.
(42) Vila H, Ferragut C, Rodríguez N, Abraldes JA. Valoración cineantropométrica dos deportistas de la selección gallega de salvamento deportivo. In: Arufe V, García JL, Domínguez A editors. II Congreso Internacional de Ciencias del Deporte. Pontevedra: Alto Rendimiento; 2008. p.1-10.

The importance of perceptual-cognitive skills in water polo players

Filipe Casanova[1,2]**, Fernando Tavares**[1,2]**, Sofia Canossa**[1]**, Maickel Bach Padilha**[1,2] **and Ricardo J. Fernandes**[1,3]

Introduction

Research on sport expertise is a fruitful domain to explore the validity of models developed in other fields. This provides a rich source of empirical evidence on the true potential of human achievement, reason why it has been defined as the ability to consistently demonstrate superior athletic performance (1, 2, 3). This research area points out that many elements of the perceptual-cognitive skills, decision-making and motor skill execution strongly influence sport performance, especially in tasks in which individuals are required to perform under strict temporal and spatial constraints (e.g. 4, 5, 6).

During invasion team sports, players need the ability to "read" the opponents intentions and perform correct techniques (e.g. to overcome opponents and score goals) aiming to achieve game purposes and win the match. Although water polo is a team sport, little empirical attention has been employed by researchers (7, 8, 9), probably because it is played in the water environment, non-using the habitual bipedal human references. Thus, studying water polo players decisions may contribute for a better understanding of their expertise, especially the mechanisms underpinning the decision-making and perceptual-cognitive skills. Differences on superior athletic performance between elite and non-elite players are typically apparent through observation, but the underlying perceptual and cognitive processes contributing to an advantage in anticipatory behavior are less evident.

Perceptual-cognitive skills refers to the ability to identify and acquire environmental information for integration with existing knowledge such that appropriate responses can be selected and executed (10). Therefore, the process of selective attention and the need to invoke a detailed

1 Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal
2 Center of Studies of Sports Games, Faculty of Sport, University of Porto, Porto, Portugal
3 Porto Biomechanics Laboratory, University of Porto, Porto, Portugal

role for knowledge structures stored in memory are considered essential to help guide the search for (and effective processing of) task specific information. Helping to contextualize the purpose of perceptual-cognitive research, a simple information-processing illustration model involving the main components in anticipation and decision-making is proposed (Figure 1; 11).

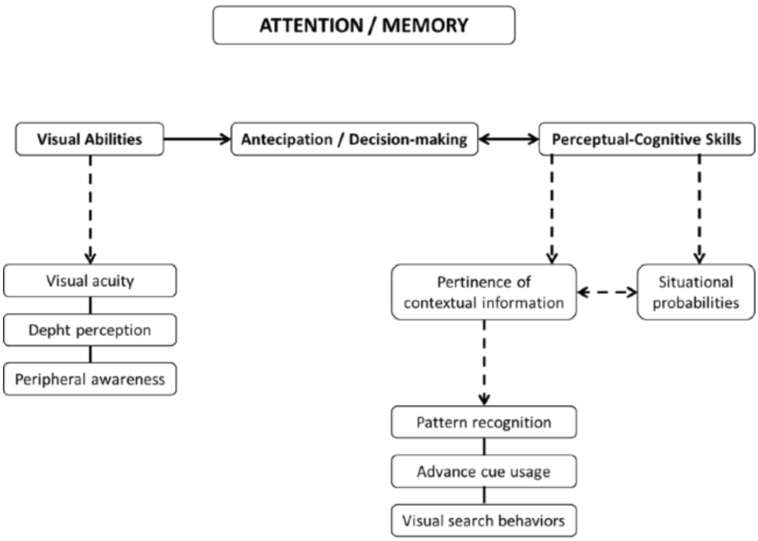


Figure 1. Brief information-processing based model of sport anticipation and decision-making skill (adapted from Williams & Ward, 2007).

Knowing the underpinning factors of elite sport performers' enhancement can help highlighting the key determinants of an effective practice, its instruction and social support networks required to performance facilitation and learning in other domains. Elite players pertinently select and accurately interpret environmental cues (i.e. perceptual component) that, combined with their faster selection of an appropriate response (i.e. decision component), allow performing a smoother and more efficient movement (i.e. motor component). Furthermore, players skilled at decision-making depend on elaborate perceptual and cognitive skills to effectively interpret complex information and formulate an appropriate action plan (12). These findings confirm previous studies in which it is stated that a distinguishing feature of experts is their adeptness on both "knowing what to do" and "doing it", while less skilled athletes may achieve some success degree with one or the other mentioned capabilities, unable to "link" both (13, 14).

Situational or strategic sports require players' fast and accurate decisions in a complex and variable environment (15, 8). These decisions occur upon information coming from different sources (e.g. ball, teammates and opponents) and space (near and far), with decision-making process occurring under pressure with opponents restricting the time and space available. In this context, the interaction dynamics between athlete and sport environment are based on the presupposition of stimulus reception from which the player emits an answer (i.e. action-reaction). Thus, players should focus their attention on the most crucial and relevant information sources to carry out their performances efficiently and successfully (16, 17).

Expert perceptual-cognitive skills

With the premise of being essential for effective anticipation and decision-making processes in sports, some researchers have highlighted superiority of skilled performers over less skilled and novice players when examined a number of perceptual-cognitive skills separately. These skills include advance visual cue utilization, pattern recall and recognition, visual search behavior and the knowledge of situational probabilities. In lay terms, it is often referred to as "game intelligence" (18).

Advance visual cue utilization

Advance visual cue use refers to a player's ability to predict accurately, based upon opponent's posture and bodily orientation, previously to a key event (19, 20). This perceptual skill is also being considered as the key factor of fast-ball sports performance because players need to perceive relevant sources under time-constrains faced throughout the game (21). On this matter, a research was conducted where experienced and inexperienced players were required to observe near "life-size" filmed sequences of five different players taking penalty kicks during preparatory stance, approach run and kicking (22). The requirement was to indicate which of the four corners of the goal the ball was to be directed, prior to temporal occlusion. Results showed that experienced players exhibited better performance only under the shortest durations (that is, pre-event or pre-contact occlusion conditions), which is in agreement with other studies results (e.g. 23, 24).

Only few researchers have attempted to identify the underlying mechanisms or even the specific perceptual information supporting the identification process that guides skillful action. This issue is usually addressed by combining the temporal occlusion approach with spatial occlusion, eye movement registration and verbal report techniques (e.g. 21, 5). In the event occlusion approach, the presumption is that if there is a decrement in performance on the trial when a cue is occluded compared to a full vision control condition, then the importance of the occluded source of information is highlighted. However, such systematic programs of research and attempts to cross-validate findings, and to extend knowledge by combining different measures, are rare in the literature.

Although this argument could not be considered, researchers have recently argued that performers are more likely to extract global motion-related information from an opponent's postural orientation than a specific information cue. The suggestion is that skilled performers use the relative motion between joints and/or limbs to guide successful performance rather than a specific cue(s) (25), which requires researchers to convert players action video images into point-light displays. These displays capture the major joint centers of body motion, which are then displayed as light points against a black background. The aim of using this technique is to remove background and contextual information presenting movement in its simplest terms (26). Moreover, contemporary methods of creating point-light (or stick figure) images using optoelectronic motion capture systems rather than video provides significant advantages in this regard (cf. 27, 28, 29).

Several researchers have suggested that: (i) both novice and skilled tennis players, for example, are leaned to change their used information when moving from normal to point-light conditions, but skilled players are much less affected than are their counterparts (30); (ii) when executing a technical skill, such as controlling a ball, the best skilled players are able to use several potential sources of sensory information (e.g. vision and proprioception) in an interchangeable manner to facilitate effective performance (31); (iii) it is possible that in certain situations skilled performers may decide not to use these cues during matches due the possible energetic cost associated with anticipation may result in performers adopting a 'wait-and-see' approach (32). Particularly in water polo, the effects of fatigue on decision making and players shooting skill have been studied by using film-based "temporal occlusion paradigm", during goal shooting skill test (8). Results showed that decision-making accuracy was superior under very high exertion conditions than lower exertion except for rest.

Pattern recall and recognition

Researchers have made extensive use of the recall paradigm to assess experts' cognitive advantage degree over lesser skilled performers. The recall paradigm comprises both static and dynamic images, portraying either a structured or unstructured task-specific display where the participant is required to recall the location of each player (33). Performance is then ascertained as the level of agreement between priori-identified features in the actual display (e.g. player positions) and the participant's recall of those features (34).

Another methodological approach termed recognition has been used to identify players' ability to recognize whether participants have previously viewed the action sequences in an earlier viewing phase. Participants' task is to quickly and accurately indicate those clips that they have or have not seen before. The literature reported that experienced players recognized previously viewed structured video clips more accurately and, consequently, were able to perceive an evolving play pattern much earlier in its development than their less experienced counterparts (35). Once again, skilled players demonstrated superior recognition skill when compared with their counterparts (34, 36, 37). If players can encode specific information to a deeper and more conceptual level, they can anticipate their opponents' intentions and plan ahead as to the most appropriate course of action.

Currently, researchers are attempting to identify the underlying mechanisms that differentiate skilled from less skilled participants. Using point-light displays, it was possible to show that skilled players maintain their superiority over less skilled players in pattern recognition performance even when players are presented as moving dots of light against a black background (6). This finding suggests that skilled players are more attuned than their counterparts to the relative motions between players and/or the higher-order relational information conveyed by such motions.

Visual search behavior

Visual search strategy is defined as the ability to pick up advanced visual cues or to identify playing patterns (19, 38). Eyes search the display or scene attempting to extract main pertinent information guiding the performers' action so that appropriate visual attention allocation precedes and determines effective motor behavior. An eye movement registration system has been used to assess visual search behavior by recording a performer's eye movements and interspersed fixations (cf.

39). Each fixation length is presumed to represent a cognitive processing degree, whereas the point-of-gaze is assumed to be representative of the most pertinent cues extracted from the environment, facilitating the decision-making process (this index is obtained by the number of visual fixations during a given period).

However, it is noticed that corresponding movements of ≤ 5° are often considered noise and statistically removed from fixation duration calculation, which typically ranges from 150 up to 600 ms (39). Researchers have recorded short (100 ms) and long fixations (1.500 ms) with corresponding movements of ≤ 1° (40). Eye movements between successive fixations, known as saccades, are believed to suppress information processing. Main research findings suggest that experts focus their gaze on more information areas of the display compared to novices, enabling them to more effectively anticipate action requirements (cf. 40, 42).

One of the earliest studies to examine the importance of visual behavior (43, 44), investigated expert and novice soccer players search patterns faced with offensive simulations requiring tactical decision-making (e.g. microstate situations – 3 vs 3, 4 vs 4 – and “set-play” conditions – free-kicks). Findings lead to the following important considerations, namely: expert players have faster movement initiation, ball-contact and total response times, and are more accurate in their decisions, as well as expert players’ better performance is attributed to an enhanced ability to recognize structure and redundancy within the display, resulting in more efficient use of available search time (this was supported by eye-movement data that showed expert visual search patterns to be economical, with fewer fixations of longer duration on selected areas of the display).

Moreover, experts are more interested in the position of the “sweeper” and any potential areas of “free” space, whereas novice players search information from less sophisticated sources such as other attackers, the goal and the ball. Some of these results were corroborated by other authors (cf. 40, 45) and even when athletes’ visual behavior is constrained by several factors (such as task nature, performers’ physical and emotional levels and the environment) experts scan the display more effectively and efficiently than their counterparts (16, 46, 42).

Maintaining gaze for an extended period of time (the so-called quiet eye period) might be the key factor in self-paced tasks where the accuracy of aiming is important. Specifically, the quiet eye period represents the elapsed time between the last visual fixation on a target and motor response initiation (47), being explored in archery (48), soccer, (49) and hockey (50). Nevertheless, despite some advantages recognizing its use on sport performance, some restrictions were pointed out when it aims dynamic situations (cf. 51), as the requirement to maintain an extended quiet-eye period prior to response initiation (which is likely to interact with the need to monitor the positions and movements of teammates and opponents) and to execute the required action prior to being challenged by an opponent (52).

So, there is an evidence suggesting that sport performers often use peripheral and central vision to extract relevant information from the display. Several researchers have noted that experts are more inclined to fixate gaze centrally in an attempt to pick up an opponent's relative motion profile using peripheral vision (23). Moreover, experts are able to anticipate an opponent's intended shot direction by fixating on relatively deterministic and proximal postural cues (such as trunk/hip rotation) before using more distal cues (e.g. racket; 6).

Knowledge of situational probabilities

This perceptual-cognitive skill has been defined as expert performers ability to extract meaningful contextual information from the event outcomes, where scientific evidence suggested that experts are more accurate to create expectations than novices on probable event to occur in any given scenario (53). Situational probabilities importance and their relationship with decision-making behavior in squash, tennis, badminton and racquetball were already examined (54, 55). In which, the results showed that players evaluated the possible event occurrences and then they used this information to maximize subsequent behavior efficiency. Players' initial anticipatory movements were guided by their expectations, with subsequent corrective or confirmatory movements being performed based on current information or contextual cues.

Moreover, Ward and Williams (56) tried to investigate elite and subelite players' requirements to predict and rank the "best passing options" available to a player in ball possession. The results founded suggest that elite players were better than their sub-elite counterparts at identifying players in the best position to receive the ball, and more accurate in assigning an appropriate probability to players in threatening and non-threatening positions. Skilled players were also better at hedging their bets, judiciously determining the importance of each potential option presented, effectively priming the search for new information and ensuring that the most pertinent contextual information was extracted from each area of the display (56).

In an attempt to clarify event probabilities in sports domain, task specificity and participant skill level, Williams (19) suggested (i) general event probability, that refers to the likelihood that opponents will typically act in a certain way given the context in question, such as the typical center-backs options when in ball possession in the middle of the field of play, the typical drive-in offensive style or the center forward play offensive predominance; and (ii) specific probabilities relate to opponents' tendencies knowledge, for example, a particular player may systematically attempt to finish offensive plays through 5m shooting action or a given center forward may always seek the back-hand shot when receiving the ball (57).

Conclusions

Although there is substantial work in the field of expertise (as previously reported), it would be of interest in future research: (i) to clarify the importance of mechanisms underlying perceptual-cognitive expertise in water polo players; (ii) to highlight the influence imposed by several constraints on the expert's performance in a near or realistic context; and (iii) to integrate simultaneously in the same research different measures of the perceptual-cognitive skills, constraints imposed by the task, the environment and the individual characteristics of the performer.

References

1. Starkes, J. L. (1993). Motor experts: Opening thoughts. In: J. L. Starkes & F. Allard (Eds.). Cognitive issues in motor expertise. Amsterdam: Elsevier Science, 3-16.
2. Ericsson, K. A., & Lehmann, A. C. (1996). Expert and exceptional performance: Evidence of maximal adaptation to task constraints. Annual Review of Psychology, 47, 273-305.
3. Ericsson, K. A. (2003). The development of elite performance and deliberate practice: An update from the perspective of the expert-performance approach. In: J. Starkes & K. A. Ericsson (Eds.). Expert performance in sport: Recent advances in research on sport expertise. Champaign, IL: Human Kinetics, 49-81.
4. Abernethy, B. (1999). The 1997 Coleman Griffith address: A juncture between psychological theory and practice. Journal of Applied Sport Psychology, 11(1), 126-141.
5. Williams, A. M., & Davids, K. (1998). Visual search strategy, selective attention, and expertise in soccer. Research Quarterly for Exercise and Sport, 69(2), 111-128.
6. Williams, A. M., Hodges, N. J., & Barton, G. (2006). Identifying patterns of play in dynamic sport tasks: The essential information underlying skilled performance. Perception, 35, 317-332.
7. Efthimios, K., Thomas, K., Maria, M., & Vasiliki, D. (1998). Cognitive, perceptual, and motor abilities in skilled basketball performance. Perceptual and Motor

Skills, 86 (3, Pt 1), 899-912.
8. Royal, K. A., Farrow, D., Mujika, I., Halson, S. L., Pyne, D., & Abernethy, B. (2006). The effects of fatigue on decision-making and shooting skill performance in water polo players. Journal of Sports Sciences, 24(8), 807-815.
9. Escalante, Y., Saavedra, J. M., Mansilla, M., & Tella, V. (2011) Discriminatory power of water polo game-related statistics at the 2008 Olympic Games, Journal of Sports Sciences, 29(3), 291-298.
10. Marteniuk, R. G. (1976). Information processing in motor skills. New York: Holt, Rinehart & Winston.
11. Williams, A. M., & Ward, P. (2007). Perceptual-cognitive expertise in sport: exploring new horizons. In G. Tenenbaum & R. C. Eklund (Eds.), Handbook of sport psychology. New York: Wiley, 203-223.
12. Williams, A. M. (2009). Perceiving the intentions of others: how do skilled performers make anticipation judgments? In R. Markus, J. Joseph, & H. Hauke (Eds.), Progress in Brain Research, vol 174, Mind and Motion: The Bidirectional Link between Thought and Action. The Netherlands: Elsevier, 73-83.
13. McPherson, S. L., & Thomas, J. R. (1989). Relation of knowledge and performance in boys' tennis: Age and expertise. Journal of Experimental Child Psychology, 48, 190-211.
14. Allard, F., & Starkes, J. L. (1991). Motor-skill experts in sports, dance, and other domains. In: K. A. Ericsson & J. Smith (Eds.) Toward a general theory of expertise: Prospects and limits. Cambridge: Cambridge University Press, 126-152.
15. Meusen, R. (2002). Fatigue during game play: a review of central nervous system aspects during exercise. In: W. Spinks, T. Reilly, & A. Murphy (Eds.). Science and Football IV. Routledge, London, 304-307.
16. Williams, A. M., Davids, K., Burwitz, L., & Williams, J. G. (1994). Visual search strategies of experienced and inexperienced soccer players. Research Quarterly for Exercise and Sport, 5(2), 127-135.
17. Roca, A., Ford, P. R., McRobert, A. P., & Williams, A. M. (2013). Perceptual-cognitive skills and their interaction as a function of task constraints in soccer. Journal of Sport & Exercise Psychology, 35, 144-155.
18. Stratton, G., Reilly, T., Richardson, D., & Williams, A. M. (2004). Youth soccer: From science to performance. London: Routledge.
19. Williams, A. M. (2000). Perceptual skill in soccer: Implications for talent identification and development. Journal of Sports Sciences, 18, 737-750.
20. Abernethy, B., & Zawi, K. (2007). Pickup of essential kinematics underpins expert perception of movement patterns. Journal of Motor Behavior, 39, 353-367.
21. Abernethy, B., & Russell, D. G. (1987). Expert-novice differences in an applied selective attention task. Journal of Sport Psychology, 9, 326-345.
22. Williams, A. M., & Burwitz, L. (1993). Advance cue utilization in soccer. In: T. Reilly, J. Clarys & A. Stibbe (Eds.). Science and Football II. London: E & FN Spon, 239-244.
23. Williams, A. M., & Reilly, T. P. (2000). Talent identification and development in soccer (Special issue). Journal of Sports Sciences, 18.
24. Starkes, J. L., Helsen, W. F., & Jack, R. (2001). Expert performance in sport and dance. In: R. N. Singer, H. A. Hausenblas & C. M. Janelle (Eds.). Handbook of

Sport Psychology. New York: Wiley, 174-201.
25. Lavalle, D., Kremer, J., Moran, A. P., & Williams, A. M. (2004). Sport Expertise. In: D. Lavalle, J. Kremer, A. P. Moran, & A. M. Williams (Eds.). Sport Psychology: Contemporary Themes. New York: Palgrave Macmillan, 139-158.
26. Cutting, J. E., & Proffitt, D. R. (1982). The minimum principle and the perception of absolute, common, and relative motion. Cognitive Psychology, 14, 211-246.
27. Hodges, N. J., Hayes, S., Breslin, G., & Williams, A. M. (2005). An evaluation of the minimal constraining information during movement observation and reproduction. Acta Psychologica, 119(3), 264-282.
28. Williams, A. M., & Ericsson, K. A. (2005). Perceptual-cognitive expertise in sport: Some considerations when applying the expert performance approach. Human Movement Science, 24 (3), 283-307.
29. Cañal-Bruland, R., Huys, R., Hagemann, N., & Williams, A. M. (2006). The effects of occlusion, neutralization, and deception of perceptual information on anticipation in tennis. Journal of Sport and Exercise Psychology, 28, S44.
30. Ward, P., Williams, A. M., & Bennett, S. J. (2002). Visual search and biological motion perception in tennis. Research Quarterly for Exercise and Sport, 73(1), 107-112.
31. Williams, A. M., Harris, M., Weigelt, C., & Scott, M. A. (2002). Age related differences in vision and proprioception during a lower limb interceptive task: The effects of skill and practice. Research Quarterly for Exercise and Sport, 73(4), 386-395.
32. James, N., Caudrelier, T., & Murray, S. (2005). The use of anticipation by elite squash players. Journal of Sports Sciences, 23(11/12), 1249-1250.
33. North, J. S., Williams, A. M., Hodges, N., Ward, P., & Ericsson, K. A. (2009). Perceiving patterns in dynamic action sequences: Investigating the processes underpinning stimulus recognition and anticipation skill. Applied Cognitive Psychology, 23, 878-894.
34. Williams, A. M., & Davids, K. (1995). Declarative knowledge in sport: a by-product of experience or a characteristic of expertise? Journal of Sport and Exercise Psychology, 17(3), 259-275.
35. Williams, A. M., Davids, K., Burwitz, L., & Williams, J. G. (1993). Cognitive knowledge and soccer performance. Perceptual and Motor Skills, 76, 579-593.
36. Smeeton, N. J., Ward, P., & Williams, A. M. (2004). Transfer of perceptual skill in sport. Journal of Sports Sciences, 19(2), 3-9.
37. Abernethy, B., Baker, J., & Côté, J. (2005). Transfer of pattern recall skills may contribute to the development of sport expertise. Applied Cognitive Psychology, 19, 1-14.
38. Henderson, J. M. (2003). Human gaze control during real-world scene perception. Trends in Cognitive Sciences, 7(11), 498-504.
39. Irwin, D. E. (1992). Visual memory within and across fixations. In: K. Rayner (Ed.). Eye movements and visual cognition: Scene perception and reading. New York: Springer-Verlag, 146-165.
40. Williams, A. M., Davids, K., & Williams, J.G. (1999). Visual Perception and Action in Sport. London: E & FN Spon.
41. Vaeyens, R., Lenoir, M., Williams, A. M., & Philippaerts, R. M. (2007). Mecha-

nisms underpinning successful decision making in skilled youth soccer players: An analysis of visual search behaviors. Journal of Motor Behavior, 39(5), 395-408.
42. Casanova, F., Garganta, J., Silva, G., Alves, A., Oliveira, J., & Williams, A. M. (2013). Effects of prolonged intermittent exercise on perceptual-cognitive processes. Medicine & Science in Sports & Exercise, 45(8), 1610-1617.
43. Helsen, W. F., & Pauwels, J. M. (1993a). A cognitive approach to visual search in sport. In: D. Brogan & K. Carr (Eds.). Visual search II. London: Taylor & Francis, 177-184.
44. Helsen, W. F., & Pauwels, J. M. (1993b). The relationship between expertise and visual information processing in sport. In: J. L. Starkes & F. Allard (Eds.). Cognitive issues in motor expertise. Amsterdam: Elsevier, 109-134.
45. Williams, A. M. (2002). Visual search behaviour in sport. (Editorial). Journal of Sports Sciences, 20(3), 169-170.
46. Vickers, J. N., & Williams, A. M. (2007). Performing under pressure: the effects of physiological arousal, cognitive anxiety, and gaze control in Biathlon. Journal of Motor Behavior, 39(5), 381-394.
47. Vickers, J. N. (1996). Visual control while aiming at a far target. Journal of Experimental Psychology: Human Perception and Performance, 22, 342-354.
48. Behan, M., & Wilson, M. (2008). State anxiety and visual attention: The role of the quiet eye period in aiming to a far target. Journal of Sports Sciences, 26, 207-215.
49. Piras, A., & Vickers, J. N. (2011). The effect of fixation transitions on quiet eye duration and performance in the soccer penalty kick: instep versus inside kicks. Cognitive Processing, 12, 245-255.
50. Panchuk, D., Vickers, J. N., & Hopkins, W. G. (2016). Quiet eye predicts goaltender success in deflected ice hockey shots. European Journal of Sport Science, doi:10.1080/17461391.2016.1156160
51. Singer, R. N. (2000). Performance and human factors: Considerations about cognition and attention for self-paced and externally-paced events. Ergonomics, 43, 1661-1680.
52. Martell, S. G., & Vickers, J. N. (2004). Gaze characteristics of elite and near-elite athletes in ice hockey defensive tactics. Human Movement Science, 22(6), 689-712.
53. Farrow, D., & Reid, M. (2012). The contribution of situational probability information to anticipatory skill. Journal of Science and Medicine in Sport, 15, 368-373.
54. Alain, C., & Girardin, Y. (1978). The use of uncertainty in racquetball competition. Canadian Journal of Applied Sport Sciences, 3, 240-243.
55. Alain, C., & Proteau, L. (1980). Decision making in sport. In: C. H. Nadeau, W. R. Halliwell, K. M. Newell & G. C. Roberts (Eds.). Psychology of motor behavior and sport. Champaign, IL: Human Kinetics, 465-477.
56. Ward, P., & Williams, A. M. (2003). Perceptual and cognitive skill development in soccer: the multidimensional nature of expert performance. Journal of Sport and Exercise Psychology, 25(1), 93-111.
57. Canossa, S., Abraldes, J.A., Soares, S. M., Fernandes, R.J. and Garganta, J.M. (2016), Vertical jump and shot speed, efficacy and accuracy in water polo, International Journal of Performance Analysis in Sport, 16, 64-79.

POLITÉCNICO DE LEIRIA | ESCOLA SUPERIOR DE EDUCAÇÃO E CIÊNCIAS SOCIAIS