



UNIVERSIDADE  
DO PORTO  
FACULDADE  
DE DESPORTO

CENTRO  
DE INVESTIGAÇÃO  
FORMAÇÃO  
INOVAÇÃO  
E INTERVENÇÃO  
EM DESPORTO  
CIFI2D



University of Porto

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# **Biophysical Evaluation of Age-Group Swimmers During a Training Season**

Academic dissertation submitted with the purpose of obtaining a doctoral degree  
in Sports Sciences according to the Decree-Law 74/2006 from March 24<sup>th</sup>

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**Porto, 2018**

Zacca, R. (2018). Biophysical Evaluation of Age-Group Swimmers During a Training Season. Doctoral Thesis in Sports Sciences. Centre of Research, Education, Innovation and Intervention in Sport. Faculty of Sport University of Porto.

**Key words:** Swimming; Age-group; Biophysics; Energetics; Biomechanics; Anthropometrics; Longitudinal

## Funding

This doctoral thesis was supported by Brazilian Federal Agency for Support and Evaluation of Graduate Education (CAPES) grant (BEX 1626/13-2/2013-2017)





## Dedications

To my grandmothers, **Edy Leão** (*in memoriam*) and **Iolanda Maciel Zacca**;

To my grandfathers; **Pierre Jorge Zacca** (*in memoriam*)

and **Waldemar Leão** (*in memoriam*);

To my mother, **Doraci Elmi Zacca**, and my father, **Jandir José Zacca**;

Thank you!



## Acknowledgments

To my family, for the patience, love and affection. Without them, it would have been impossible to achieve this goal.

To my supervisor Prof. Dr. Ricardo Fernandes for the priceless patience, guidance and friendship during this journey.

To Prof. Dr. David B. Pyne for sharing his huge experience, for the availability and also for improving my English.

To Prof. Dr. Rui Azevedo for the impressive support and enthusiasm about applied informatics and programming language.

To Prof. Dr. João Paulo Vilas-Boas for sharing his knowledge and for the support.

To Prof. Dr. Flávio Antônio de Souza Castro for opening the door for swimming research for me, for the confidence, patience and friendship.

To Prof. Dr. Argyri Toubekis for the comments, questions, friendship and new ideas.

To Leixões Sport Club Swim Team, MSc Mariana Marques and MSc Laura Freitas for the support.

To Eng. Pedro Gonçalves and Pedro Fonseca (LABIOMEPE) for sharing relevant knowledge about biomechanics and informatics.

To CAPES Foundation, Ministry of Education of Brazil, for the opportunity...*“Education is the most powerful weapon which you can use to change the world”*.

To all those were directly and indirectly involved in the data collection, Professors, fellow researchers, faculty staff, friends, swimmers and coaches.

To my true friends for the support and friendship, they know who they are!

THANK YOU!





This Doctoral Thesis is based on the following scientific papers, which are referred in the text by their Arabic and Roman numerals, respectively:

1. Zacca, R., Azevedo, R., Silveira, R. P., Vilas-Boas, J. P., Pyne, D. B., Castro, F. A. S., Fernandes, R. J. (2017). Comparison of incremental intermittent and time trial testing in age-group swimmers. *The Journal of Strength & Conditioning Research* doi:10.1519/jsc.0000000000002087.

2. Zacca, R., Azevedo, R., Figueiredo, P., Vilas-Boas, J. P., Castro, F. A. S., Pyne, D. B., Fernandes, R. J. VO<sub>2</sub>FITTING: A free and open-source software for modelling oxygen uptake kinetics in exercise. Submitted for PlosOne.

3. Zacca, R., Toubekis, A., Freitas, L., Silva, A. F., Azevedo, R., Vilas-Boas, J. P., Pyne, D. B., Castro, F. A. S., Fernandes, R. J. Effects of detraining in age-group swimmers performance, energetics, and technique. Submitted to *Journal of Sports Sciences*.

4. Zacca, R., Azevedo, R., Chainok, P., Vilas-Boas, J. P., Pyne, D. B., Castro, F. A. S., Fernandes, R. J. Monitoring age-group swimmers over a training macrocycle: energetics, technique, and anthropometrics. *The Journal of Strength & Conditioning Research*

5. Zacca, R., Azevedo, R., Junior, V.R.R., Vilas-Boas, J. P., Pyne, D. B., Castro, F. A. S., Fernandes, R. J. Biophysical follow-up of age-group swimmers during a traditional three-peak preparation program. Submitted to *The Journal of Strength & Conditioning Research*

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I. Zacca, R., Vilas-Boas, J. P., Pyne, D. B., Castro, F. A. S., Fernandes, R. J. Longitudinal Data over the International Symposium in Biomechanics and Medicine in Swimming: 1970 to 2014. XIIIth International Symposium on Biomechanics and Medicine in Swimming. Tsukuba, Japan, 2018.



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Equation 2

$$H(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases}$$

Equation 3

$$AnL = [La^-]_{net} \cdot \beta \cdot M$$

Equation 4

$$AnAL = PCr \cdot (1 - e^{-t/\tau}) \cdot M$$

Chapter 6

Equation 1

$$\dot{V}O_2(t) = A_0 + H(t - TD_p) \cdot A_p (1 - e^{-(t - TD_p)/\tau_p})$$

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$$H(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases}$$

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$$AnL = [La^-]_{net} \cdot \beta \cdot M$$

Equation 4

$$AnAL = PCr \cdot (1 - e^{-t/\tau}) \cdot M$$

## **Abstract**

Understanding more about competitive swimmers and their athletic potential requires organized, systematic and consistent evaluation. The evaluation and training control of swimmers give the coach valuable information about an athlete's improvement, stagnation, or deterioration in training and competitive performance. Assessments addressing both biological and physical aspects are usually called biophysical studies. This type of integrated approach allows a deeper understanding of the determinant variables in swimming and how they combine to enhance performance. However, few biophysical studies have been conducted on age-group swimmers, and almost all of them have been cross-sectional rather than longitudinal in design. Although cross-sectional analysis is relevant, it is not sufficient to fully describe time-course and factors influencing progression over a training period. The aim of this Thesis was to quantify change in and relationships between energetics, technique and anthropometrics characteristics in age-group swimmers during a training traditional periodization design. For that aim, we developed and validated methodological tools and protocols. Useful tools have been developed for the sports/research community, highlighting the importance of a biophysical approach to evaluate swimming performance through longitudinal studies.

We validated the 400-m test (T400) against the gold standard 7 x 200-m incremental intermittent protocol, comparing physiological and biomechanical characteristics in national level age-group swimmers. We also paved the way towards a straightforward analysis of oxygen uptake ( $\dot{V}O_2$ ) kinetics in exercise by developing a freely available and open-source software, which eases the  $\dot{V}O_2$  kinetics analysis in exercise, and can be applied for research and performance diagnostics in elite, sub-elite or recreational athletes. We then performed three longitudinal experiments. In the first longitudinal study, physiological and biomechanical effects of a typical off-season period were quantified in age-group swimmers, controlling growth and non-swimming specific physical activities performed during this training cessation period. In the second study, we quantified changes and contributions of energetic, technique and anthropometric profiles across the first training macrocycle (16-week) in a traditional three-peak swimming season. Finally, we identified changes in energetics, technique and

anthropometric profile while following age-group swimmers over a training season through a traditional three-peak preparation program. We are confident that these methodological and longitudinal studies provide relevant tools and scientific contribution to the sports and scientific community, helping to better understand the relationships between performance-related domains.

**Key words:** Swimming; Age-group; Biophysics, Energetics, Biomechanics, Anthropometrics: Longitudinal.



## Resumo

Compreender mais sobre nadadores competitivos e seu potencial atlético requer uma avaliação organizada, sistemática e consistente. A avaliação e o controle de nadadores proporcionam ao treinador informações sobre a melhoria, a estagnação ou a deterioração do atleta no treinamento e desempenho competitivo. As avaliações que abordam os aspectos biológicos e físicos são geralmente chamadas de abordagens biofísicas. Este tipo de abordagem integrada permite uma compreensão mais profunda das variáveis determinantes na natação e como elas se combinam para melhorar o desempenho. No entanto, poucos estudos biofísicos foram realizados em nadadores de grupos etários, e quase todos eles foram transversais e não longitudinais. Embora a análise transversal seja relevante, não é suficiente para descrever de maneira mais detalhada o curso e a influência dos fatores na evolução do nadador ao longo de um período de treinamento. O objetivo da tese é quantificar a mudança e as relações entre a energética, a técnica e as características antropométricas em nadadores de grupos etários durante uma periodização de treinamento tradicional. Para esse objetivo, desenvolvemos e validamos ferramentas metodológicas e protocolos. A tese oferece algumas ferramentas relevantes para a comunidade de esportes / pesquisa e destaca a importância da abordagem biofísica para avaliar o desempenho da natação através de projetos longitudinais.

Nós validamos o teste de 400 m (T400) contra o protocolo intermitente incremental de 7 x 200 m (padrão ouro), comparando características fisiológicas e biomecânicas em nadadores de grupo nacional de idade. Também abrimos caminho para permitir a análise direta da cinética consumo de oxigênio ( $\dot{V}O_2$ ) no exercício, desenvolvendo um software livremente disponível, que facilita a análise da cinética  $\dot{V}O_2$  no exercício, podendo ser aplicado para pesquisa e desempenho em atletas elite, sub-elite ou recreativos. Logo depois, realizamos três experimentos longitudinais. No primeiro estudo longitudinal, os efeitos fisiológicos e biomecânicos de um período típico de férias foram quantificados em nadadores de grupos etários, controlando o crescimento e as atividades físicas não específicas realizadas durante esse período sem treinamento. No segundo estudo, quantificamos mudanças e contribuições energéticas, técnicas

e antropométricas ao longo do primeiro macrociclo de treinamento (16 semanas) em uma temporada de natação de três picos tradicionais. Finalmente, identificamos as mudanças na energética, técnica e perfil antropométrico ao acompanhar nadadores em faixas etárias durante uma temporada de treinamento, por meio de um programa tradicional de preparação de três picos. Estamos confiantes de que esses estudos metodológicos e longitudinais fornecem relevantes ferramentas e contribuição científica para a comunidade esportiva e científica, ajudando a entender melhor as relações entre os domínios relacionados ao desempenho.

**Palavras-chave:** Natação; Grupo de idade; Biofísica; Energética; Biomecânica; Antropometria; Longitudinal.

## List of Symbols and Abbreviations

$\dot{E}$	Metabolic power
$E_{\text{tot}}$	Total energy expenditure
$[\text{La}^-]$	Blood lactate concentration
$A_0$	$\dot{V}O_2$ at rest
$A_{\text{cd}}$	Amplitude of the cardiodynamic phase
$A_{\text{er}}$	Aerobic energy
$A_{\text{nAL}}$	Anaerobic alactic energy
$A_{\text{nL}}$	Anaerobic lactic energy
ANOVA	Analysis of variance
$A_p$	Amplitude of the fast $\dot{V}O_2$ component
$A_{\text{sc}}$	Amplitude of the slow $\dot{V}O_2$ component
$A_{\text{sc\_end}}$	Amplitude of the $A_{\text{sc}}$ at the end of the T400
BMI	Body mass index
$C$	Energy cost
CI	Confidence interval
CV	Coefficient of variation
Df	Degree of freedom
$H$	Heaviside step function
HR	Heart rate
IdC	Index of coordination
kJ	Kilojoules
km	Kilometer
kW	Kilowatt
m	Meter
M	Body mass
MET	Metabolic equivalent of task
min	Minute
MRT	Mean response time
PCr	Phosphocreatine
RER	Respiratory exchange ratio

s	Second
SD	Standard deviation
SE	Standard error
SI	Stroke index
SL	Stroke length
SR	Stroke rate
Sum Sq	Sum of square
t	Time
T.U.	Arbitrary units of training
T <sub>400</sub>	400-m swimming test
TD <sub>cd</sub>	Time delay of the cardiodynamic phase
TD <sub>p</sub>	Time delay of the fast $\dot{V}O_2$ component
TD <sub>sc</sub>	Time delay of the slow $\dot{V}O_2$ component
t <sub>end</sub>	Time at the end of the T400
v	Swimming speed
$\dot{V}_E$	Minute ventilation
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_{2sc}$	Slow component of $\dot{V}O_2$ kinetics
$v\dot{V}O_{2max}$	Minimal v that elicits $\dot{V}O_{2max}$
$\beta$	Constant for O <sub>2</sub> equivalent of $[La^-]_{net}$
T <sub>cd</sub>	Time constant of the cardiodynamic phase
T <sub>p</sub>	Time constant of the fast $\dot{V}O_2$ component
T <sub>sc</sub>	Time constant of the slow $\dot{V}O_2$ component
k	Beta coefficient

## Chapter 1 General Introduction

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Understanding more about a swimmer's potential requires organized, systematic and consistent intervention programs, with the evaluation and training control providing to the coach useful scientific information on improvement, stagnation or deterioration in training and competitive performance. Since the goal of competitive swimmers is to complete the race distance as fast as possible, the technical, training and tactical factors that influence performance are attractive in swimming science. Testing swimmers during training allows coaches to follow their development, assess the effects of previous training, profile their main capabilities and predict future performance.

Training periodization is one of the most practically oriented branches of training theory and individualization is a key aspect in the sports context (Issurin, 2010). The general concept of periodization was proposed in the 1950-60s (Krestovnikov 1951; Zimkin 1961) and has been adopted by many generations of swimming coaches. The multi-year preparation is the upper level of the hierarchical periodized system, where the Olympic quadrennial cycle is the main priority. The next level of the hierarchy is represented by the macrocycles, which usually last one year but can be shortened to half a year and even less (usually defined as a one-peak annual plan). However, two-peak or even three-peak preparation models are commonly applied given diversification of competitions and increased professionalism of training (Issurin, 2010). The macrocycles are composed by three training periods, which are the most meaningful components in practice. The first component (preparatory training period) typically contains more high-volume training performed at low to moderate intensities and diversified exercises to develop general physical and technical abilities. The second component focuses on more event-specific work, and the third one, the competition period, has more race pace-specific training and reduced volume. The transition period between each season, i.e. the in-between season, is also important for age-group swimmers.

Swimming performance is multifactorial in nature in which biological and physical domains are involved (Figueiredo et al. 2013). Studies that address both domains are designated biophysical approaches, allowing a deeper understanding of the

swimming determinant variables and how they interplay to enhance performance (Pendergast et al. 2006). However, few studies have been conducted in this field, most likely related to the difficulty in conducting this type of research in the aquatic environment. Only 8% (75 from 958 published articles) of all full papers published in the industry-leading *International Symposium in Biomechanics and Medicine in Swimming* books (1971 – 2014) were longitudinal, in which 13% employed a biophysical approach (Appendix I). In fact, longitudinal studies are a small proportion of published articles in research community, which highlights the need for further studies to better understand factors influencing swimming performance. Although interdisciplinary studies are more difficult to perform, they provide valuable information for the progress of knowledge in aquatic sports.

Both oxygen uptake ( $\dot{V}O_2$ ) kinetics and metabolic contributions are reliable indicators of the metabolic profile of swimmers (Ribeiro et al. 2015). The blood lactate concentration ( $[La^-]$ ) is sensitive to changes in exercise intensity and duration (Beneke et al. 2011). Although elevated blood lactate concentration often accompanies fast swimming performances, elevated concentrations can impair subsequent exercise performance due to various metabolic perturbations (Jacobs 1986; Olbrecht 2001, Robergs et al. 2004, Juel et al. 2004; Kemp et al 2005). However, the higher the oxygen uptake per unit time the more lactate per second is combusted during exercise (Olbrecht 2011). On this basis, the maximal oxygen uptake ( $\dot{V}O_{2max}$ ) is an important physiological parameter to study the energetics, expressing the swimmers' maximal metabolic aerobic performance (Hale et al. 2008). As a marker of exercise intensity, the  $\dot{V}O_{2max}$  is considered as one of the primary areas of interest in training and performance diagnostics (Fernandes et al. 2008). Although the relationship between  $\dot{V}O_2$  and mechanical power attains a plateau despite further increases of mechanical power or swimming speed ( $v$ ) (Hill and Lupton 1923; Herbst 1928), it still generates some controversy (Howley 2007; Noakes 2008).

Longitudinal approaches in swimming require practical study protocols. In addition, large number of participants are required to ensure studies are adequately powered. Likewise, coaches seek effective, practical and reliable protocols to apply in their training routine and testing sessions. A good example of a short and practical test is the 400-m test -  $T_{400}$  (Lavoie et al. 1983; Wakayoshi

et al. 1992; Zacca et al. 2016) commonly used for evaluation and training control (Wakayoshi et al. 1993; Alberty et al. 2006; Pelayo et al. 2007). The duration of the  $T_{400}$  is similar and highly related to the time endured when swimming at the minimal  $v$  that elicits  $\dot{V}O_{2max}$  ( $v\dot{V}O_{2max}$ ). The  $T_{400}$  is situated on the severe intensity domain and provides useful information for the aerobic power development of the swimmers (Fernandes and Vilas-Boas 2012). Even though there is no study, to our knowledge, comparing the  $n \times 200$  m intermittent incremental protocol (typically 5 or 7  $\times 200$  m steps) used to determine  $v\dot{V}O_{2max}$  (Fernandes et al. 2003) and the  $T_{400}$ , the high correlation between time to perform a  $T_{400}$  and time limit at  $v\dot{V}O_{2max}$  is consistent with other studies (Costill et al. 1985; Lavoie et al. 1983; Poujade et al. 2002; Fernandes et al. 2003).

The  $\dot{V}O_2$  kinetics to the onset of exercise provides a useful assessment of the body's ability to support a change in metabolic demand and provides valuable insights into the circulatory and metabolic responses to exercise (Keir et al. 2014). However,  $\dot{V}O_2$  kinetics assessment in swimming is difficult given technical constraints imposed by the aquatic environment (Sousa et al. 2014). Up until few decades ago, the availability of technology limited swimming research: inability to follow a swimmer along the pool, the bulkiness of the equipment and the drag associated with the respiratory valve system used to collect expired gas (Toussaint et al 1988; Sousa et al. 2014). Recently, research has progressed as technology has evolved and new methods (mainly the appearance of automated portable devices) have been used to assess total energy expenditure, metabolic power, energy cost and  $\dot{V}O_2$  kinetics in ecologic swimming conditions, allowing more reliable and valid results (Ribeiro et al. 2015). However, longitudinal  $\dot{V}O_2$  kinetics assessments have not been performed in swimmers until now, probably due to these difficulties.

In most published swimming studies,  $\dot{V}O_2$  kinetics has been analyzed through mathematical modelling of constant work-rate exercise, in both on- and off-transient  $\dot{V}O_2$  responses (Whipp & Rossiter, 2005). However, there are few studies to date that have detailed the  $\dot{V}O_2$  kinetic profile of competitive swimming events (Rodríguez et al. 2003; Sousa et al. 2011; Ribeiro et al 2015). In fact, to increase  $\dot{V}O_2$  signal-to-noise ratio, at least two exercise transitions are usually performed per participant (Rossiter et al. 2002; Whipp & Rossiter, 2005; Lamarra

et al. 1987). These are time-aligned and ensemble averaged to yield a single profile per participant (Reis et al. 2010; Katch et al. 1982; Bearden et al. 2004; Smith et al. 2016). However, even only two repetitions by each swimmer are not easily measured poolside. In fact, squads are often large and facilities, equipment and sports science expertise hard to come by. Thus, instead of identical repetitions, a fixed-distance time-trial protocol is typically used.

Theoretical and practical approaches to the energetics of locomotion in swimming (Zamparo et al. 2011) report that swimming performance (the maximal attainable  $v$ ) is given by the ratio between net metabolic power ( $\dot{E}$ ) and the energy cost to swim a unit distance ( $C$ ). Aerobic and anaerobic energy contributions to  $\dot{E}$  in swimming events are independent of swimming style, gender or skill, but rely on the duration of the exercise. The  $C$  is basically determined by the hydrodynamic resistance (i.e. the higher hydrodynamic resistance the higher  $C$ ) and the propelling efficiency, i.e. the higher propelling efficiency the lower  $C$ . Thus, any influence on hydrodynamic resistance and/or propelling efficiency leads to proportional changes in  $C$ .

Stroke rate (SR), stroke length (SL), stroke index (SI) and index of coordination (IdC) are practical and reliable indicators of swimming technique (Smith et al. 2002). As swimming locomotion depends on the generation of propulsive force and the reduction of hydrodynamic drag, the capability to produce high propulsive force, while reducing the opposite drag, is decisive to achieve a certain  $v$  (Toussaint and Beek, 1992). Given that the swimmer tries to travel a given distance as fast as possible, mean  $v$  is the best measure for swimming performance (Craig et al. 1979; Craig et al. 1985; Pendergast et al. 2006), resulting from the product of SR and SL (Pendergast et al. 2006). However, the relationships between SR and SL are characterized by large within- and between- swimmer variability (Barbosa et al. 2010; Chollet et al. 1997; Seifert et al. 2007).

The swimmer does not move at constant  $v$ , as the arms, legs and trunk movements lead to intra-cyclic speed variations. In case of constant  $v$ , mean propulsion equals mean active drag. Active drag is proportional to  $v$  squared (Toussaint and Truijens, 2005). Mechanical power output is produced to overcome external forces. However, only a portion of this external force



contributes to overcoming active drag, as the swimmer's hand lacks a fixed push off point to propel the body forward. Another portion of the mechanical power applied by the hand in the water is wasted in kinetic energy imparted to the water (Zamparo et al. 2002, 2011; Toussaint and Truijens, 2005). Additionally, internal power is produced to accelerate and decelerate the limbs with respect to the center of mass. In this sense, the total mechanical power out-put is the sum of the power used to overcome drag force, kinetic power and internal power (Zamparo et al., 2011, 2002). Thus, propelling efficiency is defined as the ratio between power used to overcome drag and the total mechanical power output (Toussaint et al., 1988, 1990). A highly skilled swimmer, who has a higher propelling efficiency, can use beneficially a larger proportion of the mechanical power to overcome drag than a less skilled swimmer.

The upper inter-limb coordination is traditionally assessed by the index of coordination (IdC), which is a useful tool in quantifying motor organization in swimmers. The IdC does not indicate the motor skill of the swimmer directly but quantifies the lag time between the propulsive actions of the two upper limbs, expressed as a percentage of the overall duration of the front crawl cycle, shifting from catch-up to opposition and superposition modes (Chollet et al. 2000; Seifert et al. 2004; Seifert, 2010). Thus, the continued propulsion action in swimming depends on the correct orientation and velocity of the body segments.

Understanding that the combination of these physiological and biomechanical factors plays a relevant role in swimming, this thesis aims to monitor age-group competitive swimmers during an entire season, making an integrative assessment of biological and physical domains, checking whether a single  $T_{400}$  is sensitive enough to identify the improvement, maintenance or worsening of swimmers capacities.

The experiments in this thesis are presented in five chapters. So, after this General Introduction (**Chapter 1**), **Chapter 2** and **3** are related to methodological studies. **Chapter 2** detailed a validation study, in which biomechanical and physiological responses between the 7 x 200 m intermittent incremental protocol (Fernandes et al. 2003, Pyne et al. 2001) and the  $T_{400}$  performed in front crawl were compared. The relationship between these two tests as tools for swimming

analysis were verified from a biophysical standpoint, particularly checking the  $\dot{V}O_2$ ,  $[La^-]$ , heart rate (HR),  $v$ , SR, SL, and SI.

The mathematical modelling methods for  $\dot{V}O_2$  kinetics in swimming were explored in **Chapter 3**. Despite the required knowledge of respiratory physiology for research and performance analysts when characterising  $\dot{V}O_2$  kinetics in exercise, some existing procedures for modelling are not easily applied, since they require mastery of complex software for mathematical modelling. Although some currently available commercial software provides the end-user straightforward options for  $\dot{V}O_2$  kinetics data analysis, freely available software supported by these features is not yet available. Thus, end-users usually need to develop customised in-house tools. Given that rapid feedback from testing is necessary for coaches to better plan training sessions, tools for analysing the  $\dot{V}O_2$  response (data editing, processing, filtering and modelling) should be available, effective and relatively straightforward. Therefore, the aim of the study from **Chapter 3** was to develop and validate a freely available and open source software for dynamically editing, processing, filtering and modelling  $\dot{V}O_2$  responses to exercise.

The transition period between each season (off-season) is also important when coaches are taking a medium- to long-term approach of swimmer's development. Defined as the immediate period from which a training season ends to when the new training season begins (Sandler and Simon 2010), the transition period is valuable for keeping or even improving various biophysical factors of swimming performance. However very few studies have examined the time course of changes during a transition period between swimming seasons. Age-group swimmers typically recover for four- to six-weeks in the off-season, but this duration may differ according to the calendar of each national swimming federation (Garrido et al. 2010). There is a thin border between resting too much and too little in the off-season and the swimming community (athletes, coaches and scientists) are seeking guidance on what sort of training and recovery should be undertaken. The off-season is typically perceived as short and sweet for most swimmers given the high stress experienced during the season. Although the growth and maturation of the swimmers should be considered, non-swimming specific physical activities performed during this period cannot be overlooked.

However, this time is sometimes used to improve power, gain/loss fat mass, improve mobility, prevent injuries, and recover psychologically. Thus, in **Chapter 4**, the performance, physiological and biomechanical effects of a typical off-season period in age-group swimmers were quantified, controlling the anthropometric growth and non-swimming specific physical activities performed during this period of swimming training cessation.

The macrocycles are key elements in the traditional theory of training periodization and are usually divided into three parts. Thus, it was verified in the **Chapter 5** whether a single  $T_{400}$  is sufficiently sensitive to identify the improvement or worsening of swimmers during each period of one macrocycle (general, specific and competition period). Moreover, the relative contribution of the factors that contributed to the swimming performance were investigated. Regarding the second level of the hierarchy that is represented by the macrocycles, **Chapter 6** verified the main factors related swimming performance over an entire season and tracking the timecourse, magnitude and direction changes in anthropometric, biomechanical, maturational and physiological measures before and after each macrocycle.

Finally, a general discussion is presented, elaborating and integrating the results obtained from all these individual studies in **Chapter 7**. Main conclusions and recommendations for future research are presented in **Chapters 8** and **9**, respectively. This research will examine the front crawl technique, the most common stroke performed in both practice (training) and official swimming events, and the one that allows the highest swimming speed. Furthermore, the 400-m event, which is one of the intermediate distances in competitive swimming, provides the opportunity to investigate key relationships between swimming performance and biophysical factors.



## Chapter 2

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### **Comparison of incremental intermittent and time trial testing in age-group swimmers.**

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The Journal of Strength & Conditioning Research: June 22, 2017 - Volume  
Publish Ahead of Print - Issue - p doi: 10.1519/JSC.0000000000002087

## **Abstract**

The aim of this study was to compare physiological and biomechanical characteristics between an incremental intermittent test and a time trial protocol in age-group swimmers. 11 national level age-group swimmers (6 male and 5 female) performed a 7 x 200-m incremental intermittent protocol (until exhaustion; 30 s rest) and a 400-m test ( $T_{400}$ ) in front crawl on separate days. Cardiorespiratory variables were measured continuously using a telemetric portable gas analyzer. Swimming speed, stroke rate, stroke length and stroke index were assessed by video analysis. Physiological (oxygen uptake, heart rate and lactate concentrations) and biomechanical variables between 7<sup>th</sup> 200-m step (in which the minimal swimming speed that elicits maximal oxygen uptake -  $\dot{V}O_{2max}$  was identified) and  $T_{400}$  (time trial/fixed distance) were compared with a paired student's t-test, Pearson's product-moment correlation, Passing-Block regression and Bland-Altman plot analyses. There were high level of agreement and high correlations (r-values  $\sim 0.90$ ;  $p < 0.05$ ) for all physiological variables between the 7<sup>th</sup> 200-m step and  $T_{400}$ . Similarly, there were high level of agreements and high correlations (r-values  $\sim 0.90$ ;  $p \leq 0.05$ ) for all biomechanical variables, and only trivial bias in swimming speed ( $0.03 \text{ m}\cdot\text{s}^{-1}$ ; 2%). Primary physiological and biomechanical responses between incremental intermittent and representative time trial protocols were similar, but best practice dictates protocols should not be used interchangeably to minimize errors in prescribing swimming training speeds. The  $T_{400}$  is a valid, useful and easier to administer test for aerobic power assessment in age-group swimmers.

**Keywords** swimming · training and testing · oxygen uptake

## Introduction

Monitoring physiological and biomechanical variables during training and competition provides important insights into preparing swimmers (29,36). Maximal oxygen uptake ( $\dot{V}O_{2max}$ ) is an important variable underpinning the energetics of swimming, which is a primary area of interest in swimming training and performance diagnostics (12). The minimal swimming speed that elicits  $\dot{V}O_{2max}$  ( $v\dot{V}O_{2max}$ ) is usually assessed to provide a measure of aerobic power (2,6,10). The functional measure  $v\dot{V}O_{2max}$  combines exercise economy and  $\dot{V}O_{2max}$  into a single factor and can identify aerobic differences between swimmers. This variable has been used in cyclic sports like swimming, with either continuous or discontinuous (intermittent) incremental protocols, since similar physiological results can be obtained with both protocols (5).

The 7 x 200-m incremental intermittent swimming step protocol is primarily used to estimate the aerobic component (22,30). Nowadays, with development of automated portable devices for breath-by-breath gas exchange measurement in swimming condition (37), the 7 x 200-m incremental intermittent protocol can be used to quantify  $\dot{V}O_{2max}$ ,  $v\dot{V}O_{2max}$  and economy in swimming, providing worthwhile information on training-induced adaptations (5,10,30). This protocol, which has become the standard protocol for swimming training diagnosis, involves a graded incremental test for measurement of cardiorespiratory and metabolic responses to increasing swimming speed ( $v$ ) (10,30).

Fixed distance or time trial protocols are used frequently by the swimming community (25,40) given their applicability for training of age-group swimmers. One example is the 400-m test ( $T_{400}$ ) which has been widely used to estimate aerobic power in swimming (21,39,40) and was recently proposed for aerobic capacity assessment in age-group swimmers (40). In fact, it appears that  $\dot{V}O_{2max}$  is achieved during a  $T_{400}$ , underpinning the utility of time trial protocols to indicate performance and physiological capabilities in swimming (21,28,34). The duration of the  $T_{400}$  is comparable to the time endured when swimming at  $v\dot{V}O_{2max}$  (3,14,31) and its pace is situated on the severe intensity domain, which provides a good estimation of the aerobic power in swimming (14). Thus, it is well reported that the  $T_{400}$  is swum in sufficient time and intensity so that the swimmers can reach  $\dot{V}O_{2max}$ .

However, although practical and widely used by coaches, there is no study comparing directly the primary physiological responses between the 7 x 200-m incremental intermittent protocol (particularly at the step corresponding with  $\dot{V}O_{2max}$ ) and the  $T_{400}$ . Whether incremental intermittent and time trial protocols yield similar results and can be used interchangeably is unclear. Assuming that the physiological and biomechanical responses between both protocols are similar, a single and timesaving  $T_{400}$  should be easier to administer. This is particularly the case in age-group swimming training and testing sessions where squads are larger and sports science support is harder to come by.

From a biomechanical standpoint,  $v$  is the result of a relationship between stroke rate (SR) and stroke length (SL). This relationship is common in cyclical sports like swimming where the same motor structure is continually recruited. These two biomechanical variables are practical and reliable indicators of swimming technique (36) and easily measured poolside. These measures can be derived from video or manual timing analysis, making them attractive for coaches. A trend for SR to increase, while SL decreases from the first to the last 200-m step during an incremental intermittent front crawl protocol has been described (13,16). The stroke index (SI) is also valid and practical indicator of swimming effectiveness (36). However, it is not clear whether  $v$ , SL, SR and SI values between the step corresponding to  $\dot{V}O_{2max}$  and  $T_{400}$  are similar. Clarification of the comparability between time trial and incremental intermittent swim protocols is needed so that coaches can make an informed choice for prescribing training and evaluating changes in fitness.

There are some studies that have examined the relationships between physiological and biomechanical variables during the 7 x 200 m incremental intermittent protocol (13,16,29), but its relationship with a time trial protocol, particularly the  $T_{400}$ , is unclear. The aim of the current study was to compare the physiological and biomechanical factors between the  $T_{400}$  and the  $\dot{V}O_{2max}$  step of the 7 x 200 m incremental intermittent protocol. We hypothesized that physiological and biomechanical variables in both protocols are comparable.



## Methods

### Experimental Approach to the Problem

We compared physiological and biomechanical characteristics between an incremental intermittent and a time trial protocol in a cohort of age-group swimmers. Following a randomized order, each swimmer completed two testing sessions separated by a 24 h rest period and performed immediately after ~800-m front crawl warm up at a moderate intensity.

The first session comprised anthropometric testing, baseline measurements (after 10 min of passive recovery) and, then, a front crawl  $T_{400}$  (time trial), where physiological ( $\dot{V}O_2$ , heart rate - HR - and lactate concentrations -  $[La^-]$ ) and biomechanical ( $v$ , SR, SL and SI) variables were assessed. In the second session (after the same baseline measurements) swimmers performed a front crawl 7 x 200-m incremental intermittent protocol for  $\dot{V}O_{2max}$  and  $v\dot{V}O_{2max}$  assessments, using increments of  $0.05 \text{ m}\cdot\text{s}^{-1}$  and 30-s rest intervals (10). Initial  $v$  was established according to the individual level of fitness, set at the swimmers' individual average  $v$  of the  $T_{400}$  minus six increments of  $0.05 \text{ m}\cdot\text{s}^{-1}$ . Pacing was controlled by a visual pacer (Pacer2Swim, KulzerTEC, Santa Maria da Feira, Portugal) with flashing lights on the bottom of the 25-m pool (13). Lactate concentrations, HR, SR, SL and SI were measured on each stage.

In-water starts and open turns (without underwater gliding) were employed given physical restrictions associated with using a swimming snorkel for gas collection. The experimental protocol took place in a 25-m indoor pool (27.5°C of water temperature, 25.9°C of air temperature and 65% of air humidity) and at the same time of the day ( $\pm 1\text{h}$ ). All participants avoided vigorous exercise in the previous 24 h, were well-fed and hydrated, and abstained from caffeine for at least 3 h before testing sessions. Swimmers were encouraged verbally to reach their maximal  $v$  during  $T_{400}$  and last 200-m step of the incremental intermittent protocol. For both protocols, swimmers were familiarized during three preceding months, 2-3 times per week, with snorkels and nose clips.

### Subjects

Eleven freestyle national level age-group swimmers ( $n=11$ , 6 male and 5 female) volunteered to participate in this study. Table 1 summarizes their age, height, arm

span, body mass and pubertal maturation stage, having, at least, 5 years of training background and  $\geq 7$  units ( $\sim 5,000$ -m of volume) per week of training frequency.

**Table 1.** Subjects characteristics (mean  $\pm$  SD).

	Male (n =6)	Female (n = 5)	n = 11
Age, years	15.5 $\pm$ 0.5	15.0 $\pm$ 0.7	15.3 $\pm$ 0.6
Height, m	174.3 $\pm$ 3.7	162.4 $\pm$ 6.9	168.9 $\pm$ 8.1
Arm span, cm	179.9 $\pm$ 4.4	168.8 $\pm$ 10.8	174.88 $\pm$ 9.6
Body mass, kg	70.5 $\pm$ 3.4	55.4 $\pm$ 6.8	63.6 $\pm$ 9.3
Tanner * (I/II/III/IV/V)	(0/0/0/6/0)	(0/0/0/4/1)	(0/0/0/10/1)

\* Tanner: prepubertal (Tanner stage I), early-pubertal (Tanner stage II.), peripubertal (Tanner III), latepubertal (Tanner IV) and postpubertal (Tanner V)

This study took place in the preparatory period from the third (and last) macrocycle (43<sup>rd</sup> week) of the training season. All swimmers were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent document to participate in the study. In addition, swimmers parents or guardians provided written consent for their participation in the current study, which was approved by the ethics board of the local university and performed according to the Helsinki Declaration.

### Procedures

Pubertal maturation stage was verified by a valid and reliable self-assessment of secondary sexual characteristics (38) to determine the degree of homogeneity of the subject cohort of this study.

*Physiological variables* Respiratory and pulmonary gas-exchange data were measured breath-by-breath using a low hydrodynamic resistance respiratory snorkel and valve system (AquaTrainer®, Cosmed, Rome, Italy) as described previously (1). The AquaTrainer® was connected to a telemetric portable gas analyzer (K4b<sup>2</sup>, Cosmed, Rome, Italy) and suspended (at a 2 m height) over the water in a steel cable. The cable system was designed to minimize disturbance of the normal swimming movements. The telemetric portable gas analyzer was

calibrated before each testing session with gases of known concentration (16% O<sub>2</sub> and 5% CO<sub>2</sub>) and the turbine volume transducer calibrated with a 3 L syringe. HR was monitored continuously by a Polar Vantage NV (Polar Electro Oy, Kempele, Finland) that transmitted the data telemetrically to the K4b<sup>2</sup> portable unit during both swimming protocols. A capillary blood sample (5 µL) for [La<sup>-</sup>] was collected from an earlobe before exercise, during the 30-s recovery intervals of the incremental intermittent protocol and immediately after both protocols at the first, third, fifth, and seventh min of the recovery period ([La<sup>-</sup>]<sub>peak</sub>). Samples were analyzed by a Lactate Pro analyzer (Arkay, Inc, Kyoto, Japan)

*Biomechanical variables* A surface video camera at the 25-m indoor pool (50 Hz, Sony® Handycam HDR-CX130 Japan) was used to record and analyze variables from both protocols. To exclude the influence of turning, the effective  $v$  of each swimmer was measured over 10 m within two points at 7.5 m distance from each end of the pool. Thus,  $v$  of each swimmer was measured from the time taken to cover the middle 10 m of each length ( $v = d/t_{10}$ , where  $d = 10\text{-m}$  and  $t_{10} = \text{time for the } 10\text{-m}$ ). Stroke rate (SR) was computed from the time taken to complete three consecutive stroke cycles and SL was calculated from the ratio of the  $v$  and the corresponding SR. Finally, SI, as a measure of swimming effectiveness, was calculated by multiplying  $v$  by SL (15). All these variables were measured during each 25 m of both the 7 x 200 m incremental intermittent protocol and T<sub>400</sub>.

### **Data analysis**

For both protocols, errant breaths (caused by swallowing, coughing and/or signal interruptions) were omitted from the  $\dot{V}O_2$  analysis by only including those were within  $\dot{V}O_2$  local mean  $\pm 4$  SD (26). Subsequently, individual breath-by-breath  $\dot{V}O_2$  responses were time averaged every 10 s and smoothed using a 3-breath moving average (7). Oxygen uptake ( $\dot{V}O_2$ ), heart rate (HR), respiratory exchange ratio (RER) and minute ventilation ( $\dot{V}_E$ ) at the end of both protocols were calculated as the average from the last 60 s of exercise. The  $\dot{V}O_2$  at the end of the 7 x 200-m incremental intermittent protocol was defined as  $\dot{V}O_{2max}$  through a case-by-case inspection of the plateau in  $\dot{V}O_2$  despite an increase in  $v$ , added to volitional exhaustion (37). The  $v\dot{V}O_{2max}$  was estimated as the  $v$  corresponding to the first step of the 7 x 200 m incremental intermittent protocol that elicited  $\dot{V}O_{2max}$ . It is well-established that swimmers can sustain  $v$  for sufficient duration such that the kinetics reach  $\dot{V}O_{2max}$  in the severe intensity domain during this protocol

(3,14,31). Thus, to standardize the variables compared in this study,  $\dot{V}O_2$  at the end of  $T_{400}$  was compared with  $\dot{V}O_{2max}$ .

### **Statistical analysis**

A sample size of 11 subjects was deemed adequate (software G\*Power 3.1.9.2© Heinrich-Heine-Universität Düsseldorf, Germany) assuming statistical power of 85% and  $\alpha$  error probability of 0.05. Pubertal development distribution was described by frequencies and Fisher's test was used to assess differences between males and females for Tanner status. The assumption of normality was verified with the Shapiro–Wilk test. Mean and SD for descriptive analysis were obtained and reported for all studied variables. A paired t-test was used to assess differences between the swim protocols. Possible gender vs protocols effects were verified a priori with Factorial ANOVA.

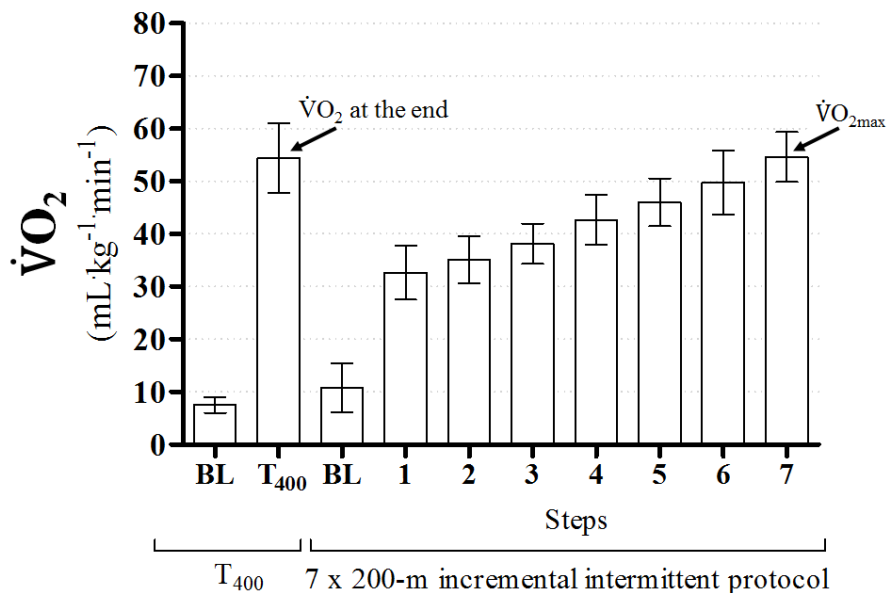
Pearson's product–moment correlation coefficient was used to quantify the degree of association between variables measured during 7 x 200-m incremental intermittent protocol and  $T_{400}$ , and interpreted as follows: <0.40 poor, 0.40-0.75 fair to good and >0.75 excellent (17). Validity was assumed when the correlation between variables was >0.90, according to established guidelines (19). However, while correlation analysis indicates the degree to which two variables are associated, it does not necessarily indicate the extent to which values agree or disagree. Thus, agreement between both swimming protocols (one of them used as the reference) was evaluated using both Passing-Bablok regression (MedCalc Software, version 11.6, Mariakerke, Belgium) and Bland–Altman plot analysis (GraphPad Prism version 6.00 for Windows, GraphPad Software, La Jolla California USA). The Passing-Bablok regression analysis (27) is a scatter diagram of variables measured with two different methods. Variables are deemed proportional when the 95% confidence interval of the slope includes 1 value and the 95% confidence interval of the intercept includes the zero value. Random differences were verified by the residual standard deviation, a measure of the random differences between the two methods. The Cusum test for linearity was used to evaluate how well a linear model fitted the data. A small P value (< 0.05) indicates that the relationship between the two measurements is non-linear and the Passing-Bablok method deemed not applicable (27). The Bland-Altman plot (4) was used to assess the absence of systematic differences between two measurements. The mean of the two measurements was plotted against the

difference between them with 95% of the differences expected to lie within the limits of agreement (mean  $\pm$  1.96 SD). The inspection of the slope of the linear regression (Bland–Altman plot) between both protocols (to check for systematic error) was performed. Significance level alpha was established at 0.05.

## Results

No differences ( $p = 0.45$ ) in pubertal maturation stage were identified between males and female subjects. Preliminary data analysis indicated no differences between genders when comparing both protocols. No interaction between gender and protocol was detected for any variable ( $p = 0.27$  to  $0.99$ ), i.e., the results obtained from both protocols were similar for male and female. Thus, male and female data were subsequently pooled and analyzed as a single group.

The estimated  $\dot{V}O_2$  values of 7 x 200-m incremental intermittent protocol and  $T_{400}$  are presented in Figure 1. The  $v\dot{V}O_{2max}$  was identified during the 7<sup>th</sup> 200-m step (duration of the stage:  $151 \pm 7s$ ) for all 11 swimmers. A very large correlation was observed between the performance of  $T_{400}$  ( $311 \pm 17 s$ ) and  $v\dot{V}O_{2max}$  ( $r = -0.79$ ; 95%CI  $-0.94$  to  $-0.36$ ,  $p = 0.004$ ).



**Figure 1.**  $\dot{V}O_2$  values (mean  $\pm$  SD) among baseline (BL), end of  $T_{400}$  and 7 x 200-m incremental intermittent protocol (7<sup>th</sup> step =  $v\dot{V}O_{2max}$ ).

Table 2 shows the physiological and biomechanical variables obtained in both protocols, particularly the comparison between 7<sup>th</sup> 200-m step ( $v\dot{V}O_{2max}$ ) and  $T_{400}$ ,

with no differences being evident. Correlations (all  $p < 0.0001$ ) were excellent for absolute  $\dot{V}O_{2\max}$  ( $r = 0.98$ ), relative  $\dot{V}O_{2\max}$  ( $r = 0.94$ ), HR ( $r = 0.92$ ) and  $\dot{V}_E$  ( $r = 0.94$ ), good for  $[La^-]$  ( $r = 0.69$ ;  $p < 0.05$ ) and poor for RER ( $r = 0.31$ ;  $p = 0.35$ ). Although correlations for biomechanical variables (all  $p < 0.0001$ ) were excellent for SL ( $r = 0.90$ ), SR ( $r = 0.89$ ) and SI ( $r = 0.92$ ), and good for  $v$  ( $r = 0.78$ ;  $p < 0.05$ ), larger differences were identified in SL,  $v$  and SI between 7<sup>th</sup> step of the 7 x 200-m incremental intermittent protocol ( $v\dot{V}O_{2\max}$ ) and the  $T_{400}$  (Table 2).

**Table 2.** Physiological and biomechanical variables obtained at the step corresponding to  $v\dot{V}O_{2\max}$  and  $T_{400}$

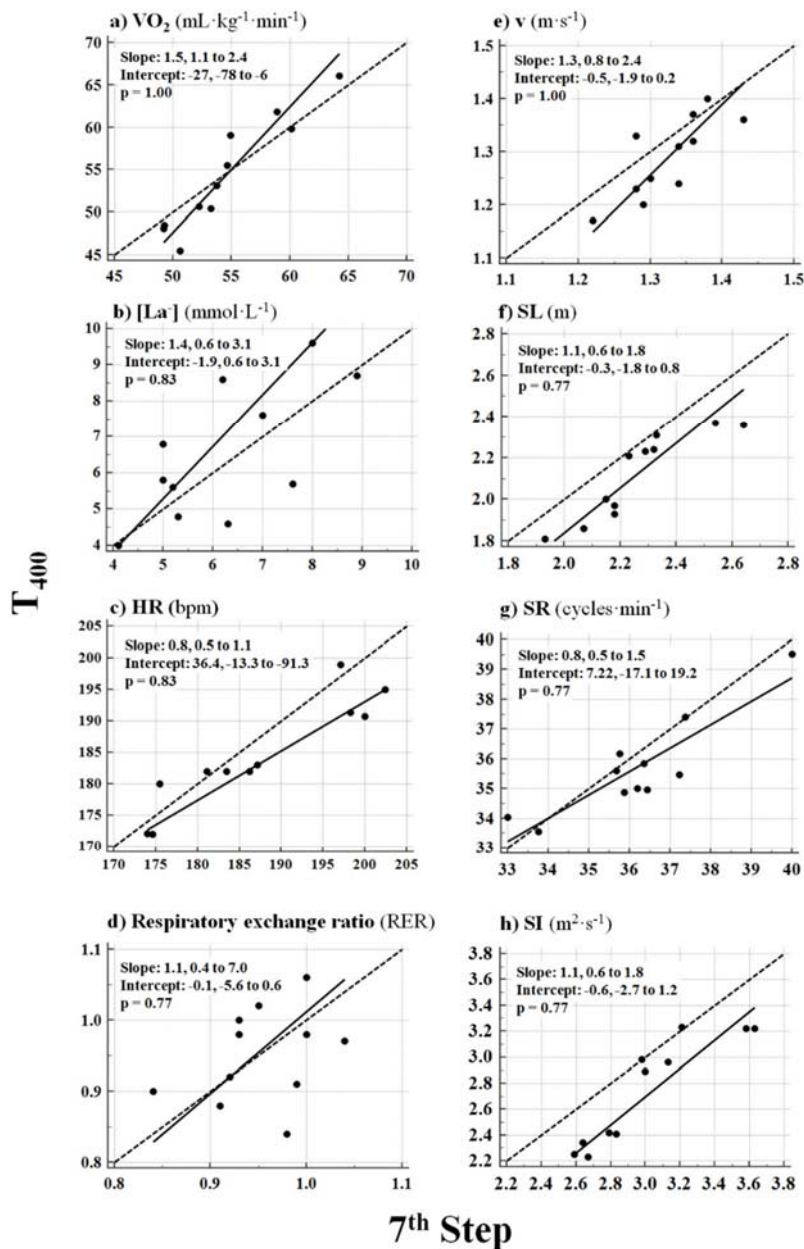
	7 <sup>th</sup> x 200-m ( $v\dot{V}O_{2\max}$ ) mean $\pm$ SD	$T_{400}$ mean $\pm$ SD	Mean difference (95% confidence interval)	Correlation coefficient (r)
$\dot{V}O_2$ , L $\cdot$ min <sup>-1</sup>	3.48 $\pm$ 0.61	3.47 $\pm$ 0.70	0.01 (-0.10 to 0.12)	0.98**
$\dot{V}O_2$ , mL $\cdot$ kg <sup>-1</sup> $\cdot$ min <sup>-1</sup>	54.6 $\pm$ 4.7	54.4 $\pm$ 6.6	0.2 (-2.0 to 2.0)	0.94**
HR, bpm	187 $\pm$ 10	184 $\pm$ 9	2.8 (-0.03 to 5.60)	0.93**
RER	0.95 $\pm$ 0.05	0.95 $\pm$ 0.06	0.002 (-0.046 to 0.051)	0.31
$\dot{V}_E$ , L $\cdot$ min <sup>-1</sup>	101 $\pm$ 21	98 $\pm$ 26	3 (-4 to 9)	0.94**
$[La^-]$ , mmol $\cdot$ L <sup>-1</sup>	6.2 $\pm$ 1.5	6.5 $\pm$ 1.9	-0.3 (-1.2 to 0.6)	0.69*
$v$ , m $\cdot$ s <sup>-1</sup>	1.32 $\pm$ 0.05 <sup>†</sup>	1.29 $\pm$ 0.07 <sup>†</sup>	0.03 (0.005 to 0.067)	0.78*
SL, m	2.3 $\pm$ 0.2 <sup>††</sup>	2.1 $\pm$ 0.2 <sup>††</sup>	0.1 (0.1 to 0.2)	0.90**
SR, cycles $\cdot$ min <sup>-1</sup>	36.1 $\pm$ 2.5	35.7 $\pm$ 1.7	0.5 (-0.1 to 1.0)	0.89**
SI, m <sup>2</sup> $\cdot$ s <sup>-1</sup>	3.0 $\pm$ 0.4 <sup>†</sup>	2.4 $\pm$ 0.4 <sup>†</sup>	0.3 (0.1 to 0.4)	0.91**

Oxygen uptake ( $\dot{V}O_2$ ); heart rate (HR), respiratory exchange ratio (RER); minute ventilation ( $\dot{V}_E$ ); lactate concentrations ( $[La^-]$ ); swimming speed ( $v$ ); stroke length (SL); stroke rate (SR) and stroke index (SI).

t-test (p-value): <sup>†</sup>  $p < 0.05$ ; <sup>††</sup>  $p \leq 0.0001$

Correlation coefficient (p-value): \*  $p < 0.05$ ; \*\*  $p \leq 0.0001$

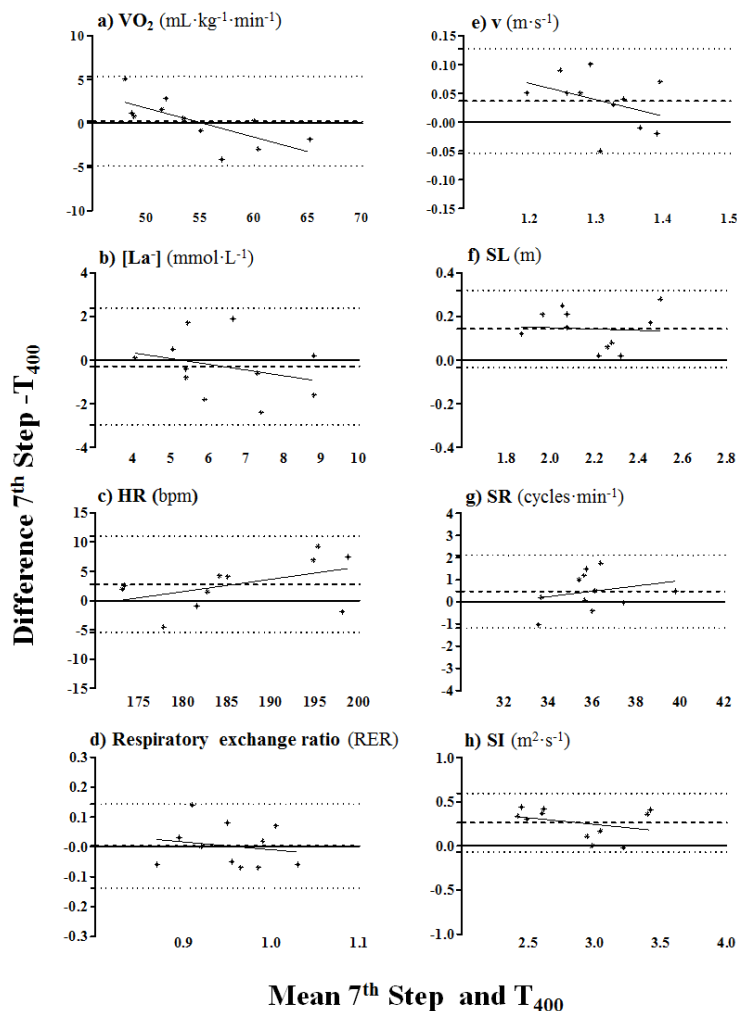
Passing-Bablok regression between physiological and biomechanical variables from the 7<sup>th</sup> step of the 7 x 200-m incremental intermittent protocol ( $v\dot{V}O_{2\max}$ ) and the  $T_{400}$  are presented in Figure 2.



**Figure 2.** Passing-Bablok regression of physiological and biomechanical variables obtained during the 7<sup>th</sup> step of the 7 x 200-m incremental intermittent protocol ( $v\dot{V}O_{2\text{max}}$ ) and the  $T_{400}$ . The solid and dashed lines indicate the regression equation and the identity, respectively. The regression equation ( $y = a + bx$ ) shows if there is constant [regression line's intercept (a)] and proportional [regression line's slope (b)] difference and respective confidence intervals of 95% (95% CI). If the 95% CI for intercept includes value zero, it means that there was no significant difference between the intercept value and zero, and thus there was no constant difference between two protocols. Where the 95% CI for the slope includes the value of one then difference between obtained slope value and value one is deemed not significant, and thus there was no proportional difference between both protocols. Thus, we could assume that  $x = y$  and that there was no significant difference between protocols. A  $p$  value  $> 0.05$  indicates that the relationship between the two measurements is linear and the Passing-Bablok method deemed applicable.

The 95% confidence intervals of the slope obtained from the Passing-Bablok regression analysis included or were very close to 1. Similarly, the 95% confidence intervals of the intercept included, or were very close to 0 value. The Cusum test showed linearity for all regressions between both protocols ( $p > 0.05$ ) (Figure 2).

Similarly, the Bland-Altman plots revealed a consistent distribution with all values inside the limits of agreement and a small bias observed for all the selected physiological and biomechanical variables. The limits of agreement, bias and slope of the linear regression (Bland–Altman plot) between physiological and biomechanical variables obtained at the 7<sup>th</sup> step of the 7 x 200-m incremental intermittent protocol ( $\dot{V}O_{2max}$ ) and the  $T_{400}$  are presented in Figure 3.



**Figure 3.** Limits of agreement (black dotted lines), bias (black dashed line) and slope of the linear regression of physiological and biomechanical variables between the 7<sup>th</sup> step of the 7 x 200-m incremental intermittent protocol ( $\dot{V}O_{2max}$ ) and the  $T_{400}$ .



Systematic error (linear regression) was identified only for  $\dot{V}O_2$  in Bland-Altman plot ( $r = 0.50$ ; 95%CI - 4.9 to 5.4,  $p = 0.01$ ), indicating that swimmers who have a  $\dot{V}O_2$  greater than  $\sim 55 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  reach slightly higher values of  $\dot{V}O_2$  during  $T_{400}$  than in the 7<sup>th</sup> 200-m step ( $v\dot{V}O_{2\text{max}}$ ).

## Discussion

We compared the primary physiological and biomechanical responses between an incremental intermittent and a time trial protocol. The  $T_{400}$  is valid and easier to administer, particularly for age-group swimmers, since it provides direct evidence of the strong relationship with  $v\dot{V}O_{2\text{max}}$  (3,14,31). However, although outcome measures from both protocols are similar, we advise not to use them interchangeably to avoid errors in prescribing swimming training speeds.

Performance and physiological characteristics of the  $T_{400}$  have been studied extensively. Lavoie et al. (21) reported a high correlation ( $r=0.92$ ,  $p < 0.01$ ) between the Douglas bag and 20 s post-exercise recovery methods for estimating  $\dot{V}O_{2\text{max}}$  in swimming with the  $T_{400}$ . In the early 2000s, Rodríguez et al (34) suggested that  $T_{400}$  yields similar and high correlated  $\dot{V}O_2$  values to maximal incremental treadmill running ( $r = 0.87$ ;  $p \leq 0.001$ ) and maximal incremental cycle ergometer test ( $r = 0.83$ ;  $p \leq 0.001$ ). Since then,  $T_{400}$  is a method to assess aerobic power and prescribe swimming training intensities (40). However, a validation study was needed to determine whether the  $T_{400}$  have similar physiological and biomechanical estimates to the 7<sup>th</sup> 200-m step ( $v\dot{V}O_{2\text{max}}$ ), and it was confirmed in our study. The level of agreement between both protocols was confirmed for all physiological and biomechanical variables with the Bland and Altman and Passing-Bablok regression analysis. However, the estimated small difference in  $v$  ( $0.03 \text{ m}\cdot\text{s}^{-1}$  equating to 0.9 s per 50 m) between both protocols suggests a lack of direct interchangeability. Whichever protocol is chosen (7 x 200-m incremental intermittent protocol or  $T_{400}$ ), we recommend keeping the same for subsequent testing to avoid small but meaningful differences in  $v$  during training sessions.

*Physiological variables* The minimal swimming speed that elicits  $\dot{V}O_{2\text{max}}$  ( $v\dot{V}O_{2\text{max}}$ ) contains both  $\dot{V}O_{2\text{max}}$  and swimming economy in one term (2). Training sets performed at  $v\dot{V}O_{2\text{max}}$  can improve both  $\dot{V}O_{2\text{max}}$  and swimming economy (12). In fact, there was an inverse relationship between the  $T_{400}$  and  $v\dot{V}O_{2\text{max}}$ .

These results are in agreement with other recent studies (9,31), i.e. the performance of  $T_{400}$  is related with both aerobic power ( $\dot{V}O_{2max}$ ) and swimming economy (2,14,31).

Comparison of ventilatory variables between two incremental protocols (continuous and intermittent) for  $\dot{V}O_{2max}$  and  $v\dot{V}O_{2max}$  assessment in swimming was first conducted a decade ago (5). The incremental intermittent protocol was deemed suitable for both  $\dot{V}O_{2max}$  and  $v\dot{V}O_{2max}$  assessment. At the same time, the  $\dot{V}O_2$  kinetics during a  $T_{400}$  was examined (33), where  $\dot{V}O_{2peak}$  was directly correlated with  $v$  proving to be a good predictor of swimming performance. The  $v$  of  $T_{400}$  has been used for training and research, on the basis that the duration of the  $T_{400}$  is similar to the time endured when swimming at  $v\dot{V}O_{2max}$  (14,31) and also because  $\dot{V}O_{2max}$  is achieved during a  $T_{400}$  (21,28,34). Our study goes beyond these previous studies by validating the usefulness of  $T_{400}$  for age-group swimmers, confirming a high level of agreement for all physiological variables between the  $T_{400}$  and 7<sup>th</sup> 200-m step (the one in which  $v\dot{V}O_{2max}$  was identified).

There were only trivial bias in estimates of physiological variables between the 7<sup>th</sup> 200-m step ( $v\dot{V}O_{2max}$ ) and the  $T_{400}$  (Table 2), with  $[La^-]$  values in agreement with other data on age group swimmers (13). High correlations for  $\dot{V}O_{2max}$ , HR and  $\dot{V}E$ , and a high reproducibility for all physiological variables in Passing-Bablok regression and Bland-Altman analysis indicate close agreement between the 7<sup>th</sup> step of the 7 x 200 m incremental intermittent protocol ( $v\dot{V}O_{2max}$ ) and the  $T_{400}$ . Linear regression analysis (Bland-Altman plot) indicated a systematic error for estimation of  $\dot{V}O_2$  between the 7<sup>th</sup> step ( $v\dot{V}O_{2max}$ ) and  $T_{400}$  (Figure 3, a). Although high reproducibility and accuracy were identified for all physiological variables, systematic error for  $\dot{V}O_2$  most likely relates to limitations of the fixed distance protocols used in this study.

Time to accomplish fixed distance protocols should address two main requirements. First, exercise durations cannot be too short, i.e. swimming bouts for which time to reach fatigue is less than 2 min do not allow enough time for the  $\dot{V}O_2$  to increase to a maximal value. Secondly, swimming intensity needs to lie within the severe domain, since it is characterized by attainment of  $\dot{V}O_{2max}$  (18). In fact, the 7<sup>th</sup> step from the incremental intermittent protocol was performed at severe intensity domain in our study (8), since it lies with the step in which  $\dot{V}O_{2max}$

was achieved. Likewise, the range between the minimum and maximum times of 7<sup>th</sup> 200-m step ( $v\dot{V}O_{2max}$ ) (~139 and 163 s) agrees with the minimal duration required for attainment of  $\dot{V}O_{2max}$ . Assuming that different step lengths might affect the  $\dot{V}O_{2max}$  assessment,  $\dot{V}O_2$  values from incremental intermittent protocols with 200, 300 and 400-m length steps were compared, and observed that 200-m distances are valid for  $\dot{V}O_{2max}$  (11). Moreover, the minimum and maximum performances of  $T_{400}$  (~293 and 342 s, respectively) are in agreement with the time endured at  $v\dot{V}O_{2max}$  reported in the literature (14). Swimming intensity of  $T_{400}$  is similar to the intensity of the 7<sup>th</sup> 200-m step ( $v\dot{V}O_{2max}$ ), given trivial differences between the physiological variables (Table 2). Swimming coaches and scientists can be advised that the  $T_{400}$  should produce similar physiological responses to the 7<sup>th</sup> step from the incremental intermittent protocol.

The constraints of finding an adequate sample of national level age-group swimmers with homogeneous pubertal maturation led us to pool and analyze male and female swimmers as a combined single group. However, although this methodological limitation should be considered, preliminary data analysis with all variables indicated that the results obtained from both protocols were similar for male and female swimmers. Coaches can prescribe similar interval-training workouts for male and female swimmers with equal training background, since the main  $\dot{V}O_2$  kinetics parameters are comparable at similar relative exercise intensities (32).

*Biomechanical variables* The biomechanical profile of a swimmer detailing relationships between SR, SL, SI and performance is a relevant and practical tool for swimming coaches. During incremental exercise,  $v$  rises with the combination of an increase in SR and a decrease in SL (16). Likewise, a decline in  $v$  is almost completely accounted by a decrease in SL, given that the SR remains stable (or is slightly higher in last 100-m) during a  $T_{400}$ , highlighting a loss of technical effectiveness (20,24,35). We also observed loss of efficiency from the first to the last 200 m step of the 7 x 200 incremental intermittent protocol and during the  $T_{400}$ , with high correlations and level of agreements observed between  $T_{400}$  and the 7<sup>th</sup> 200-m step ( $v\dot{V}O_{2max}$ ) for all biomechanical variables. This is an important result, since both physiological and biomechanical results were similar between protocols, which makes the  $T_{400}$  even more helpful for the assessment of age-

group swimmers. Coaches could apply the  $T_{400}$  in their workouts as a feasible, short and practical protocol for age-group swimmers.

It is important to verify the validity of the  $T_{400}$  in reproducing the biomechanical responses of the 7<sup>th</sup> 200-m step ( $v\dot{V}O_{2max}$ ), since  $T_{400}$  is commonly used due to its practicality for training and testing (24,40). Correlations and reproducibility were very high for all biomechanical variables, in spite of a trivial difference in paired t-test for  $v$ , SL and SI. Oliveira et al. (24) observed higher bias for  $v$  ( $1.39 \pm 0.6 \text{ m}\cdot\text{s}^{-1}$  and  $1.34 \pm 0.08 \text{ m}\cdot\text{s}^{-1}$  for the 7<sup>th</sup> 200-m step and  $T_{400}$ , respectively) than our study (Table 2), but it was not enough to infer a significant difference. Differences observed in SL and SI most likely relate to the difference in the fixed distance protocols used in this study (200 vs 400-m). As young swimmers have a well-developed oxidative metabolism and disadvantages in activities predominantly supported by anaerobic metabolism when compared to adults, this lower anaerobic system participation could have contributed to the failure in maintaining technical patterns during  $T_{400}$ , decreasing SL and consequently  $v$  and SI (23,35).

However, despite these differences, the high correlation and reproducibility observed in Passing-Bablok regression and Bland-Altman plots between both protocols confirms their comparability and the validity of using the  $T_{400}$ . Estimates from both methods lies within the severe intensity domain (similar  $\dot{V}O_{2max}$ ). Nevertheless, if we calculate  $v\dot{V}O_{2max}$  training paces for 100, 200 and 400-m distances throughout both protocols ( $1.32$  and  $1.29 \text{ m}\cdot\text{s}^{-1}$  for the 7<sup>th</sup> 200-m step and  $T_{400}$ , respectively), the difference ( $0.03 \text{ m}\cdot\text{s}^{-1}$ ) is in fact  $\sim 2 \text{ s}$  (1:16 and 1:18),  $\sim 3 \text{ s}$  (2:32 and 2:35) and  $\sim 7 \text{ s}$  (5:03 and 5:10) for 7<sup>th</sup> 200-m step and  $T_{400}$  (minutes:seconds) respectively. Thus, the use of the protocols interchangeably is not recommended, since minor bias in  $v$  can occur when prescribing training sets.

In conclusion, incremental intermittent and time trial (fixed distance) protocols are broadly comparable in terms of physiological and biomechanical characteristics, although use both interchangeably is not recommended. The  $T_{400}$  is a valid and easier option for aerobic power assessment in age-group swimmers, since it showed similar physiological and biomechanical responses to the 7<sup>th</sup> 200-m step

( $\dot{V}O_{2max}$ ). These outcomes confirm the viability of the  $T_{400}$  in monitoring the fitness, performance and technical characteristics of age-group swimmers.

### **Practical applications**

Attractive protocols for age-group swimmers should be characterized for having strong ecological validity, that is, reflecting real swimming conditions, unlike laboratory settings. In this way, researchers compared two methods (a new method with an established one) to determine whether the new approach is worth employing. Given the strong relationship observed between  $T_{400}$  and  $\dot{V}O_{2max}$ , we consider the  $T_{400}$  valid. Although the 7 x 200-m incremental intermittent protocol provides additional worthwhile information on training-induced adaptations over the  $T_{400}$ , a single test is more convenient and easy to conduct for assessing  $\dot{V}O_{2max}$  in age-group swimmers. Age-group swimming coaches could use the  $T_{400}$  intermittently throughout the training season, but we do not recommend using the 7 x 200-m incremental intermittent protocol ( $\dot{V}O_{2max}$ ) and  $T_{400}$  interchangeably, since using the same protocol will provide a better control (reducing the errors) of estimated training velocities. Future studies should investigate the effects of gender and swimming technique/distance specialty on 7 x 200 m incremental intermittent protocol and  $T_{400}$ . Further work to examine the small bias in  $v$ , SL and SI during time to exhaustion at  $\dot{V}O_{2max}$  between both protocols would be also be useful.

### **Acknowledgments**

The authors thank the support of coaches, swimmers, and all those who were involved in this study. This work was funded by the by CAPES Foundation, Ministry of Education of Brazil, Brasília—DF, Brazil. The authors declare that they have no conflict of interest.



## Chapter 3

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### **VO<sub>2</sub>FITTING: A free and open-source software for modelling oxygen uptake kinetics in exercise.**

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Submitted to PlosOne

## **Abstract**

*Background:* The assessment of oxygen uptake ( $\dot{V}O_2$ ) kinetics is a valuable non-invasive way to evaluate cardiorespiratory and metabolic response to exercise. *Objective:* Developing, describing and testing an online  $\dot{V}O_2$  fitting tool (VO<sub>2</sub>FITTING) for dynamically model and analyse  $\dot{V}O_2$  kinetics. *Methods:* VO<sub>2</sub>FITTING was developed in Shiny, a web application framework for R language. Validation  $\dot{V}O_2$  datasets with noisy and non-noisy data were developed and applied to the most widely-used models (n=7) for describing different intensity transitions to verify concurrent validity. Subsequently, we have conducted an experiment illustrating how VO<sub>2</sub>FITTING can be used to model  $\dot{V}O_2$  kinetics, particularly during a transition from rest to severe exercise intensity. Twenty age-group swimmers (14.6 ± 0.9 years old) performed a single front crawl 400-m time-trial swim test (T400). Data was fitted through mono- and bi-exponential models without any constraint for parameter estimates. Bootstrapping statistical analysis (1000 samples) was applied for estimating parameters and ANOVA F-test was used to compare the goodness of fit. *Results:* Perfect fits were observed, and parameter estimates perfectly matched the known inputted values for all available models (standard error = 0; p < 0.001). Bi-exponential model best fitted T400  $\dot{V}O_2$  response for 75% (p<0.05) of the swimmers and it was similar to the mono-exponential model in the remaining swimmers. No substantial differences in model fit were evident between genders. *Conclusion:* Our experiment with age-group swimmers illustrated some applications and feasibilities of VO<sub>2</sub>FITTING. Likewise, validation  $\dot{V}O_2$  datasets, supplementary swimming and running-related data highlighted other available options of VO<sub>2</sub>FITTING. The VO<sub>2</sub>FITTING is valid, free and open-source software with long-term utility for characterising  $\dot{V}O_2$  kinetics in exercise, which was developed to help the research and performance analysis community.



## Introduction

Successful sport competitive performance is the result of a complex interaction between many factors, which often involves testing procedures to evaluate effects of training programs [1]. From a diversity of tests and variables, sports scientists characterise dynamic profiles (kinetics) of cardiorespiratory variables to better understand the control mechanisms of muscle energetics and oxidative metabolism. These profiles can inform the preparation of the annual training plan, periodization of training mesocycles, microcycles and prescription of individual training sets [2].

The rate at which oxygen uptake ( $\dot{V}O_2$ ) responds to metabolic demand changes at the onset of exercise is dependent on the capacity of the cardiorespiratory and muscular systems to react appropriately [3]. Understanding  $\dot{V}O_2$  kinetics involves quantifying physiological mechanisms responsible for the dynamic  $\dot{V}O_2$  response to exercise (on-transient kinetics) and its subsequent recovery (off-transient kinetics) [4]. Quantifying on-transient  $\dot{V}O_2$  kinetics, which has a different and eventually higher responsiveness to training stimuli than maximal oxygen uptake ( $\dot{V}O_{2max}$ ), has gained popularity in understanding the regulation of the  $O_2$  transport/utilization system during exercise [5, 6, 7].

The  $\dot{V}O_2$  assessment in exercise, followed by  $\dot{V}O_2$  profile mathematical modelling, is a useful non-invasive method for studying muscle oxidative metabolism. The  $\dot{V}O_2$  response following the onset of a specific intensity can be defined by the underlying exercise-intensity domain (low to moderate, heavy, severe and extreme) [8, 9, 10]. At the low to moderate intensity domain (i.e. below and at the anaerobic threshold),  $\dot{V}O_2$  begins to increase within the first breath (Phase I or cardiodynamic component). Following a brief time delay, there is an exponential increase of  $\dot{V}O_2$  ~15-20 s later (Phase II, fundamental or primary component, p) to achieve a subsequent steady state (Phase III) [11, 12, 13]. At the heavy intensity domain, after the cardiodynamic phase,  $\dot{V}O_2$  continues rising before a secondary  $\dot{V}O_2$  elevation becomes apparent after ~90-120 s (the slow component of  $\dot{V}O_2$  kinetics,  $\dot{V}O_{2sc}$ ). This increase is overlapped on the faster primary response until a delayed steady state is attained, exhaustion ensues or exercise ends [11, 14, 15]. At even higher work rates, at the severe intensity domain,  $\dot{V}O_2$  cannot be stabilized, rising rapidly and exponentially to  $\dot{V}O_{2max}$  [13,

16]. At this intensity domain,  $\dot{V}O_{2sc}$  is more pronounced compared to heavy exertion, rising inexorably until fatigue ensues [17]. Finally, in the extreme domain, the work rate is so intense that the task finishes before the  $\dot{V}O_{2max}$  can be achieved [4, 18]. At this intensity,  $\dot{V}O_2$  is characterized by the development of a fast component with insufficient time for a  $\dot{V}O_{2sc}$  to appear [19].

The  $\dot{V}O_2$  kinetics analysis allows an immediately and separately assessment of relative contribution of the energy systems delivery, used substrate and time the endured during exercise [19]. Higher exercise tolerance is essentially associated to changes on fast and slow components of the  $\dot{V}O_2$  kinetics, particularly the time constant of the primary component ( $\tau_p$ ) and the amplitude of the slow component ( $A_{sc}$ ), which are relevant for performance analysis [19, 20]. A smaller value for  $\tau_p$  results in faster attainment of steady state, while delayed or more slowly developing  $A_{sc}$  is associated with enhanced exercise tolerance. In some exercise modalities, like swimming, both parameters are comparable between females and males at same relative intensity transitions, which is important advice for coaches from a practical standpoint despite interindividual variation in  $\dot{V}O_2$  response to swim training [20].

Given that rapid feedback from testing is necessary for coaches to better plan training sessions, tools for analysing the  $\dot{V}O_2$  response (data editing, processing, filtering and modelling) should be available, effective and relatively straightforward. However, free and open-source software supported by these features is not yet available. Thus, end-users usually need to develop customised in-house tools, which require mastery of complex for mathematical modelling, despite the mandatory and basic knowledge of respiratory physiology. Therefore, the aim of the current study was twofold: (i) developing, describing and evaluating a  $\dot{V}O_2$  fitting tool for dynamically editing, processing, filtering and modelling  $\dot{V}O_2$  responses to exercise; and (ii) using this  $\dot{V}O_2$  fitting tool, to verify the goodness of fit between different models and respective confidence intervals of  $\dot{V}O_2$  kinetics parameters obtained from one swimming event to illustrate some of the software capabilities. Also, we added some related data analyses in the supporting information (S1 File), illustrating some available options on  $VO_2FITTING$ , which are useful for research and performance analysis in sports.

## Methods

We developed a software (VO<sub>2</sub>FITTING) and conducted an experiment illustrating how it can be used to edit, process, filter and model  $\dot{V}O_2$  responses in exercise, particularly in swimming. We used raw data from a pool-based fixed-distance even-paced time-trial swim test (400-m swim test, T400) performed at the severe intensity domain [21], without any constraint for parameter estimates (see *Constraining parameters in curve fitting section*; S1 File)

## Subjects

Twenty age-group swimmers (ten female) volunteered to participate in this study. Their main physical and training frequency characteristics were:  $14.9 \pm 0.9$  and  $14.2 \pm 0.9$  y, body mass  $67.2 \pm 3.6$  and  $52.7 \pm 6.9$  kg, height  $170.8 \pm 2.6$  and  $160.0 \pm 6.3$  cm, arm span  $174.5 \pm 8.1$  and  $164.1 \pm 10.5$  cm (mean  $\pm$  SD for male and female swimmers, respectively),  $\geq$ six training sessions per week and  $\geq$ five years of competitive experience. Pubertal maturation stage [22] was similar for both males and females (late pubertal to post pubertal). All subjects were informed about the benefits and risks of participating in the investigation prior to signing an institutionally approved informed consent form. In addition, swimmers parents or guardians provided written consent for their participation in the current study that was approved by the ethics board of the local university and performed according to the Helsinki Declaration.

## **Development of VO<sub>2</sub>FITTING software: source code, requirements, availability and license**

We developed the VO<sub>2</sub>FITTING, a free and open-source software which provides a dynamic analysis of the  $\dot{V}O_2$  responses to exercise. VO<sub>2</sub>FITTING offers functionalities that confer enough flexibility to compare simultaneously several cardiodynamic responses with sufficient precision to meet researcher and performance analyst requirements. VO<sub>2</sub>FITTING runs online, inside a browser, requiring a Shiny server, which can be configured for local or shared access by multiple users, thus not requiring an internet connection while modelling  $\dot{V}O_2$  kinetics (S1 File). News about the application, source code, installation instructions and other documentation can be verified on the landing page ([https://shiny.cespu.pt/vo2\\_news/](https://shiny.cespu.pt/vo2_news/)). The latest version of VO<sub>2</sub>FITTING will be

permanently available in the repository. The source code of VO<sub>2</sub>FITTING is released under a GNU General Public License version 3 (GPL-3; <https://www.r-project.org/Licenses/GPL-3>). Software which are covered by this license are free and open-source, even after each new release. This license ensures that everyone can use the software and modify it.

## **Experimental Methodology**

Prior to the experiment, swimmers were familiarised for three months, 2-3 times per week, with snorkel and nose clip. The experimental protocol took place in a 25-m indoor pool [water (27 °C) and air (25°C) temperature, and 65% relative humidity]. Swimmers were tested at the same time of the day, properly fed and hydrated, and instructed not to perform strenuous exercise on the day before. Following a randomised order, each swimmer performed ~800-m front crawl warm up at moderate intensity, and soon after, a T400. The T400 is commonly used to assess aerobic power in swimmers, given its pace is situated on the severe intensity domain [14]. Although the breathing snorkel used for respiratory gas collection does not add additional hydrodynamic drag [23], in-water starts and open turns (without underwater gliding) were used given its physical restrictions. Subsequently, the VO<sub>2</sub>FITTING software was applied (S1 File) for editing, processing and modelling  $\dot{V}O_2$  response from each swimmer. The goodness of fit of different models and respective confidence of  $\dot{V}O_2$  kinetics parameters were verified.

## **Experimental measurements**

Respiratory and pulmonary gas-exchange data were measured breath-by-breath using a low hydrodynamic resistance respiratory snorkel and valve system (AquaTrainer®, Cosmed, Rome, Italy) [24]. The AquaTrainer® was connected to a telemetric portable gas analyser (K4b<sup>2</sup>, Cosmed, Rome, Italy) and suspended at a height of 2 m over the water in a steel cable (designed to minimize disturbance of the normal swimming movements) [23]. The telemetric portable gas analyser and turbine volume transducer were calibrated (following the manufacturer instructions) before each testing session with gases of known concentrations (16% O<sub>2</sub> and 5% CO<sub>2</sub>) and 3 L syringe, respectively.

## Models and parameters estimation

To increase  $\dot{V}O_2$  signal-to-noise ratio, at least two exercise transitions are usually performed per participant [25, 26, 27]. These are time-aligned and ensemble averaged to yield a single profile per participant [28, 29, 30, 31]. This feature is available in the  $\dot{V}O_2$ FITTING, of which an example is shown (S1 File). However, it was not used in the current experiment, since even only two repetitions by each swimmer are not easily measured poolside. In fact, squads are often large and facilities, equipment and sports science expertise hard to come by. Thus, instead of identical repetitions, a fixed-distance time-trial protocol is commonly used. Thus, we employed an experimental model where each swimmer ( $n=20$ ) performed a single 400-m front crawl even-paced time-trial swim test (T400), in randomized order, same warm-up, arousal, time of day and time of testing within the training period.

The  $\dot{V}O_2$  kinetics parameters were estimated including the precision of estimation (confidence limits) by bootstrapping [32, 33, 34] (see Statistical analysis section for more details). Parameter estimates and goodness of fit of each model (mono- and bi-exponential) were only analysed with raw data.

The first 20 s of data after the onset of exercise (cardiodynamic phase) were not considered for  $\dot{V}O_2$  kinetics analysis. For each swimmer, the on-transient was modelled with mono- and bi-exponential models (Equations 1 and 2), characterising the exercise  $\dot{V}O_2$  response during the T400:

$$\dot{V}O_2(t)=A_0+H(t-TD_p) \times A_p(1-e^{-(t-TD_p)/\tau_p}) \quad (1)$$

$$\dot{V}O_2(t)=A_0+H(t-TD_p) \times A_p(1-e^{-(t-TD_p)/\tau_p})+H(t-TD_{sc}) \times A_{sc}(1-e^{-(t-TD_{sc})/\tau_{sc}}) \quad (2)$$

where  $\dot{V}O_2(t)$  ( $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) represents the relative  $\dot{V}O_2$  at the time  $t$ ,  $A_0$  is the  $\dot{V}O_2$  at rest (2 min average;  $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ).  $A_p$  and  $A_{sc}$  ( $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ),  $TD_p$  and  $TD_{sc}$  (s), and  $\tau_p$  and  $\tau_{sc}$  (s) are respectively the amplitudes, the corresponding time delays and time constants of the fast and slow  $\dot{V}O_2$  components.  $H$  represents the Heaviside step function (Equation 3) [35]:

$$H(t)=\begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases} \quad (3)$$

$\dot{V}O_2$  at the end was calculated as the average of the last 60 s of exercise for both models. Since the asymptotic value of the second function is not necessarily reached at the end of the exercise, the amplitude of the  $A_{sc}$  at the end of the T400 ( $A_{sc\_end}$ ) was also calculated (Equation 4) (see “Auxiliary reports” at S1 File) [20, 36]:

$$A_{sc\_end}=A_{sc}(1-e^{-(t_{end}-TD_{sc})/T_{sc}}) \quad (4)$$

where  $t_{end}$  is the time at the end of the T400. The  $A_{sc}$  was calculated as the difference between the  $\dot{V}O_2$  at the end (average of the last 60 s) and “ $A_p+A_0$ ” (using the available option from `VO2FITTING`). The  $\dot{V}O_2$  response from both mono-and bi-exponential functions was fitted by a routine based on nonlinear least-square regression and implemented in `VO2FITTING` [37] (for details, see S1 File). The R (R Core Team, 2015), a free software environment for statistical computing and graphics, was used to perform all the computations of the current study, with the support of the Shiny package [38] ([www.rstudio.com/products/shiny/shiny-server/](http://www.rstudio.com/products/shiny/shiny-server/)).

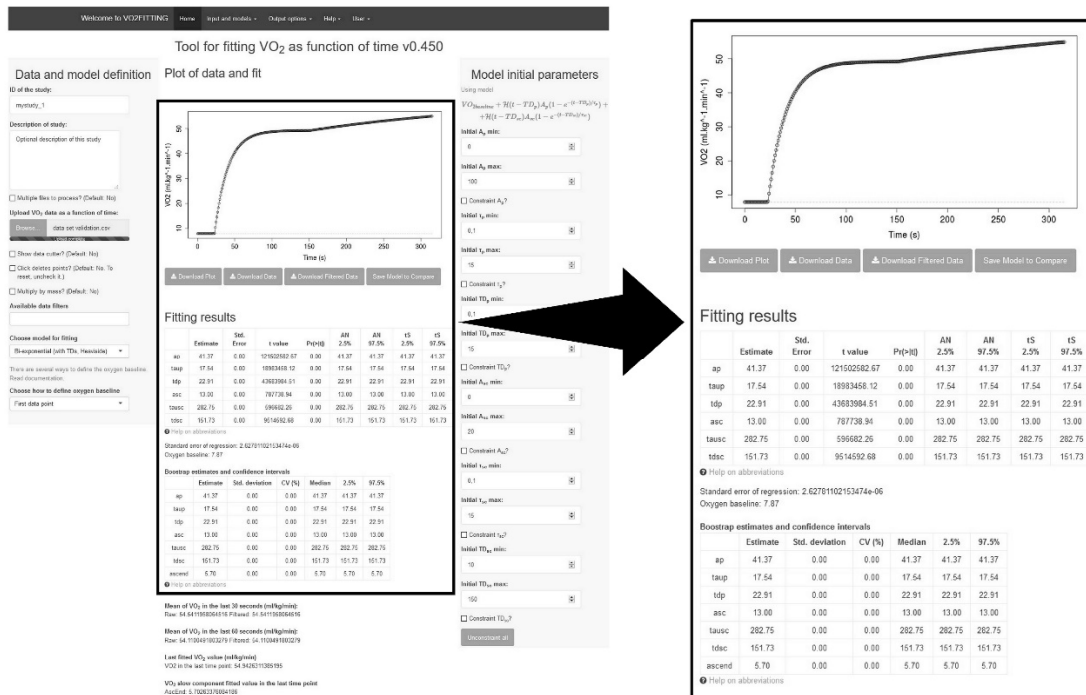
### Statistical analysis

Concerning software concurrent validation, datasets with noisy (Gaussian) and non-noisy were developed for seven different models, describing different intensity transitions (3 mono-exponential, 2 bi-exponential, 1 tri-exponential and 1 logistic model; see S1 File for details), both provided as downloadable spreadsheets in the supporting information (S2 File). Subsequently,  $\dot{V}O_2$  data outputs as a function of time were created through these files and uploaded in the application, verifying whether the fitted parameters perfectly matched the known input values. Moreover, all these spreadsheets (S2 File) can be employed by the end-user to generate different datasets, even with different ranges of input

values and suitable for specific scenarios, to verify and validate the software response. We used bootstrapping with 1000 samples (with replacement from the observed residuals), adjustable in the interface, for estimating parameters of mono- and bi-exponential fitting models for each swimmer T400 [32, 33, 34]. Mean, standard deviation, coefficient of variation, and percentile confidence intervals (2.5 and 97.5%) were calculated for each parameter estimate (Bootstrapping analysis is available in VO<sub>2</sub>FITTING; see *Output Options* on S1 File). To verify the goodness-of-fit for both mono- and bi-exponential models, Shapiro-Wilk (residuals distribution) and ANOVA F-test (with respective residuals sum of the squared from the differences between both models) were applied. A level of significance 0.05 was used in all tests.

## **Results**

$\dot{V}O_2$  output data as a function of time obtained from the validation datasets (S2 File) generated perfect fits. Moreover, the parameter estimates perfectly matched the known inputted values for all seven available models (standard error = 0;  $p < 0.001$ ). An example of a bi-exponential model validation dataset uploaded in VO<sub>2</sub>FITTING is displayed in Fig1, with parameter estimates perfectly matching the known inputted values.



**Fig. 1** An example of (bi-exponential) validation dataset uploaded from VO<sub>2</sub>FITTING (middle). Upper-left and right corners show *data and model definition* menu, and the *model initial parameters* menu (without any constraint for parameter estimates).

Table 1 shows an overview of all parameter estimates for each model, particularly the mean parameter estimates for all swimmers (fitted individually), standard deviation, 95% confidence interval and mean coefficient of variation. The mean swimming performance in T400 was 5:15 ± 0:20 min:s (males: 5:04 ± 0:06 min:s; females; 5:27 ± 0:17 min:s).

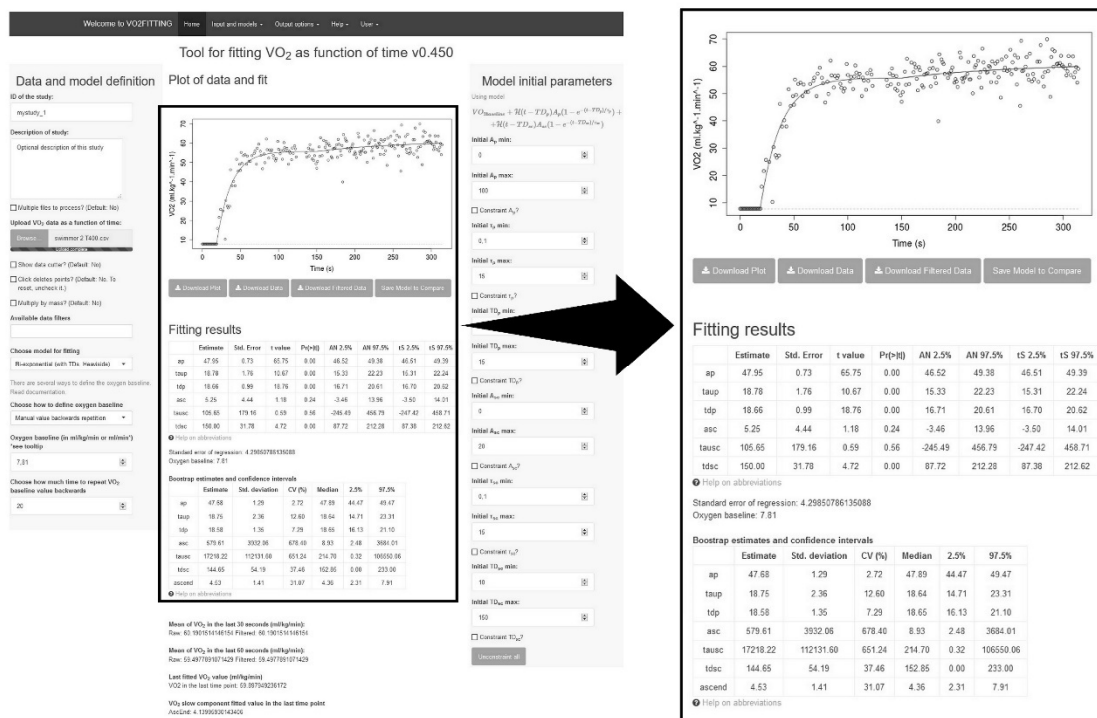


**Table 1.** Estimated  $\dot{V}O_2$  related parameters obtained from mono- and bi-exponential models (mean  $\pm$  SD).

(N = 20)	Mono-exponential	Bi-exponential
$A_0$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	8.8 $\pm$ 3.4	8.8 $\pm$ 3.4
$A_0$ (mL·min <sup>-1</sup> )	528 $\pm$ 204	528 $\pm$ 204
$A_p$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	44.1 $\pm$ 7.0	40.0 $\pm$ 7.3
$A_p$ (mL·min <sup>-1</sup> )	2644 $\pm$ 419	2398 $\pm$ 438
95%CI (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	42.9 to 45.4	35.0 to 42.9
CV (%)	1.5%	5.3%
$TD_p$ (s)	20.8 $\pm$ 6.1	24.0 $\pm$ 6.8
95%CI (s)	13.9 to 26.9	16.5 to 30.4
CV (%)	18.5%	16.3%
$T_p$ (s)	26.5 $\pm$ 12.0	16.5 $\pm$ 7.4
95%CI (s)	18.3 to 36.4	8.1 to 28.1
CV (%)	16.6%	36.4%
$A_{sc\_end}$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	-	6.95 $\pm$ 1.8
$A_{sc\_end}$ (mL·min <sup>-1</sup> )	-	417 $\pm$ 108
95%CI (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	-	3.3 to 12.4
CV (%)	-	34.8%
$TD_{sc}$ (s)	-	137 $\pm$ 23
95%CI (s)	-	10.9 to 239.3
CV (%)	-	45%
$\dot{V}O_2$ at the end (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	55.1 $\pm$ 6.4	55.1 $\pm$ 6.4
$\dot{V}O_2$ at the end (mL·min <sup>-1</sup> )	3303 $\pm$ 384	3303 $\pm$ 384

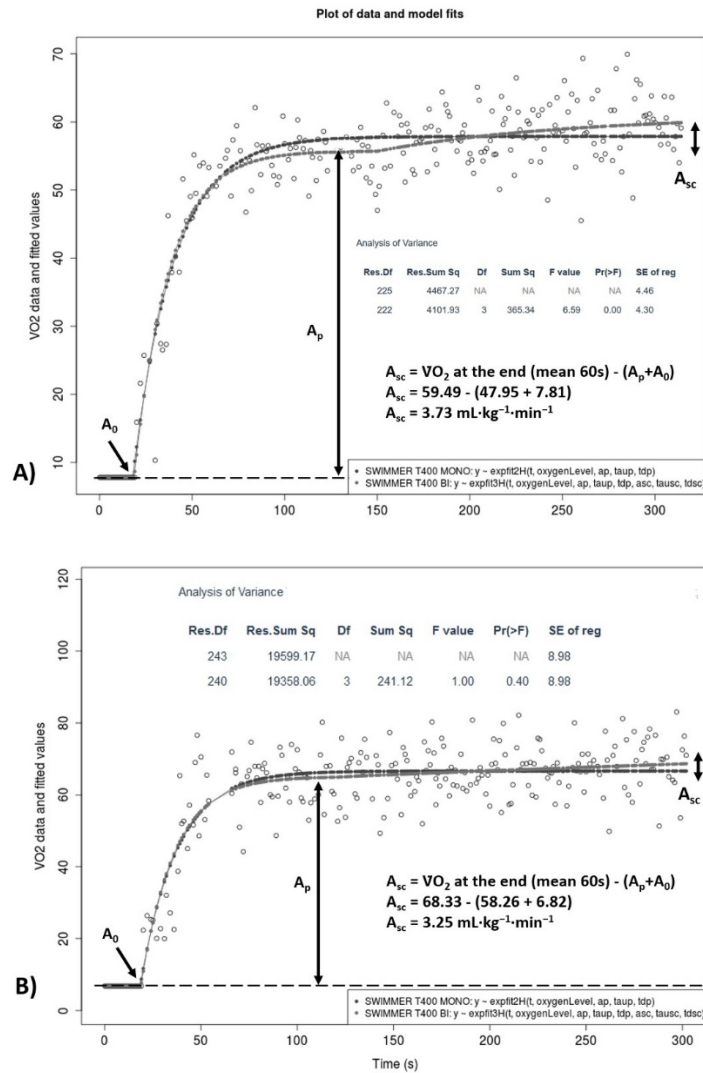
$A_0$  is the  $\dot{V}O_2$  at rest;  $A_p$  and  $A_{sc\_end}$ ,  $TD_p$  and  $TD_{sc}$  are respectively amplitudes and corresponding time delays of the fast and slow  $\dot{V}O_2$  components. The  $T_p$  is the time constant of the fast  $\dot{V}O_2$  component. CV (%) and 95%CI are the mean coefficient of variation and 95% confidence interval for each mean parameter estimate, respectively.

Fig 2 shows the  $\dot{V}O_2$ FITTING home menu with an example of a T400 modelled  $\dot{V}O_2$  response (bi-exponential), indicating that it is endowed with a wide range of available tools for modelling the on-transient  $\dot{V}O_2$  kinetics. Software options include joining multiple observations, data filtering, specific data point deletions, multiple options related to  $A_0$ , several fitting models, output reports and constraint fitting ranges for the parameters when the fitting fails with default values. A screenshot from the bottom of the  $\dot{V}O_2$ FITTING home menu detailing residuals plots to evaluate the goodness of fit of the T400 modelled  $\dot{V}O_2$  response (bi-exponential) of the same swimmer presented in Fig 2 is showed on supporting information (S1 File)



**Fig. 2** VO<sub>2</sub>FITTING home menu with an individual example of a T400 modelled  $\dot{V}O_2$  response (bi-exponential) in the middle. *Data and model definition*, and *model initial parameters* menu without any constraint for parameter estimates are presented in upper-left and right corner, respectively.

Fig 3 shows two examples of mono- vs. bi-exponential fits comparisons from a typical T400  $\dot{V}O_2$  response (with corresponding residual plots for each model). On the top of Fig 3, the F-test indicated that bi-exponential model was superior for this swimmer. Likewise, bi-exponential model best fitted for 15 swimmers, presenting a smaller residual sum of squares and standard error of regression ( $p < 0.05$ ). The mono-exponential model was not superior for any swimmer since the F-test did not show differences between both models for the remaining five swimmers, as illustrated on the bottom of Fig 3. The  $A_{sc}$  calculated as the difference between the  $\dot{V}O_2$  at the end (average of the last 60 s) and “ $A_p + A_0$ ” was  $6.3 \pm 2.7$  mL·kg<sup>-1</sup>·min<sup>-1</sup>. Model comparison was similar between gender, since the bi-exponential model best fitted for 70 and 80% of males and females, respectively.



**Fig. 3** Examples of goodness-of-fit analysis between mono- and bi-exponential models of a typical T400  $\dot{V}O_2$  response from two swimmers. A) bi-exponential model being superior; B) No difference between mono- and bi-exponential models. ANOVA F-test (with respective residuals sum of the squared from the differences between both models) showed on the top of both graphics. \* Res.Df: residual degree of freedom; Res.Sum Sq: residual sum of square; Df: degree of freedom; Sum Sq: sum of square; SE of reg: standard error of regression.

## Discussion

Performance analysts spend several hours to provide objective information for athletes and coaches, helping them to understand and improve performance in sports. The use of technology and software by these professionals is crucial. However, they should give fast performance diagnosis, since coaches need immediate feedback for readjusting training sessions. To this end, dynamic and

feasible fitting tools for  $\dot{V}O_2$  kinetics analysis should be available. In this study,  $\dot{V}O_2$  data outputs were uploaded from noisy and non-noisy datasets to assess the concurrent validity of available models from VO<sub>2</sub>FITTING, and some experiments were performed to illustrate its applicability.

$\dot{V}O_2$  kinetics analysis enables a non-invasive assessment of the effectiveness of training programs, providing relevant information about exercise tolerance determinants. Some commercial software require mastery of complex software for mathematical modelling (e.g. Matlab, Mathworks, Natick, USA, [www.mathworks.com](http://www.mathworks.com); LabVIEW™, National Instruments, Austin, TX, <http://www.ni.com/en-us/shop/labview.html>), despite mandatory and basic knowledge of respiratory physiology required for research and performance analysts in sports [12, 39, 40]. The VO<sub>2</sub>FITTING solves that constraint, allowing straightforward analysis of  $\dot{V}O_2$  kinetics in exercise with a feasible graphical interface. Although some of the available commercial software also provide the end-user relatively straightforward options for  $\dot{V}O_2$  kinetics data analysis (e.g. Origin, OriginLab, Northampton, MA, USA, [www.originlab.com](http://www.originlab.com); GraphPad Prism, GraphPad Software, San Diego, CA, USA, <https://www.graphpad.com/>; SigmaPlot, Systat Software, San Jose, CA; [www.sigmaplot.co.uk](http://www.sigmaplot.co.uk)), VO<sub>2</sub>FITTING goes further since it is freely available and open-source software with long-term utility for the research and performance analysis communities.

Every  $\dot{V}O_2$  breath-by-breath signal has non-uniformities in the underlying breathing pattern [28], which are relevant for its variability, particularly if corrections for the differences between alveolar and mouth O<sub>2</sub> exchanges are not taken into consideration [41]. Fluctuations in gas exchange are even more pronounced in swimming given the constraint related to breathing pattern (e.g during front crawl there is a specific moment to inspire and other to expire). Unlike swimming, athletes can decide to breath when they want during running or cycling. Likewise, swallowing and coughing can also generate fluctuations in gas exchange, resulting in variability or ‘noise’ around the mean  $\dot{V}O_2$  response [16, 28, 42]. These errant breaths can degrade the signal quality since they are not components of the response, influencing the confidence in parameter estimates and their interpretation [43]. Thus, the high coefficients of variation of critical estimated parameters also highlight some issues regarding our current

experimental design. We added an example in the supporting information (S1 File), in which a comparison between swimming and running was performed at the same relative intensity. By this example, it was observed that the coefficients of variations from parameter estimates were predominantly higher in swimming than running, thus illustrating some of the available options of VO<sub>2</sub>FITTING, useful for research and performance analysis in elite, sub-elite or recreational athletes.

VO<sub>2</sub>FITTING is also provided by the most widely used filters for  $\dot{V}O_2$  kinetics analysis, which are detailed described in the supporting information (S1 File). In this regard, we presented some related data illustrating quantitatively and graphically some of these filters, like *rolling standard deviation*, *averaging in a box* and *moving average*. Other filters like *interpolation every 1-s* and moving mean are also available on VO<sub>2</sub>FITTING (S1 File). Although commonly used, there is little consensus on how to fit and treat swimming  $\dot{V}O_2$  kinetics data [8, 9]. However, even assuming that errant breaths are not from the actual transient  $\dot{V}O_2$  kinetics, editing  $\dot{V}O_2$  signal should be made with caution using a priori established criteria [26]. As standard values for data editing have not been established yet, some authors prefer to err on the side of less stringency, particular by excluding data that lie more than four standard deviations away from the mean [10, 26, 42]. Although symmetrical high-low pairing of such close in time breaths may offset fitting effects, it is arguable whether the fitting model should be conducted on filtered or raw data, since more stringency (allowing more 'errant' data points) could exert a major influence on the parameters estimation. For example, substantial errors can be observed during fast  $\dot{V}O_2$  kinetic responses given the limited volume of data in the transient region [26]. Since model fitting  $\dot{V}O_2$  kinetics parameters are necessarily estimates, adequate characterization of its response cannot be satisfactorily retrieved from artificially filtered data where noise is deliberately attenuated [28, 44]. Thus, to avoid any constraint, parameter estimates and goodness of fit between different models were only analysed with raw data.

It is unclear whether time aligning and ensemble averaging  $\dot{V}O_2$  data to yield a single transition can affect the physiological meanings of parameter estimates.

Some of the currently used modelling methods required subjects to perform several transitions, reducing noise and improving parameter estimates [29, 30, 31, 32]. Although VO<sub>2</sub>FITTING also allows this type of signal processing, a bootstrapping method was chosen to estimate parameters (with respective coefficient of variations) using samples from a unique transition for each participant since it provides reliable information about the estimated parameters [33, 34, 35]. In fact, the estimated coefficients of variation for A<sub>p</sub> (mono:1.5% vs bi-exponential: 5.3%) and TD<sub>p</sub> (mono: 19% vs bi-exponential: 16%) in the current study were relatively suitable for both models. However, the low accuracy verified in estimation of the two critical parameters on the bi-exponential model (i.e., A<sub>sc\_end</sub>: 35% and TD<sub>sc</sub>: 45%) seems to be related to the pronounced fluctuations in  $\dot{V}O_2$  kinetics in swimming and the inherently low signal-to-noise ratio changes, which typically decrease from childhood through adulthood [45].

Understanding the physiological significance of both  $\dot{V}O_2$  fast and slow components during exercise is an essential skill of researchers and performance analysts [19, 46, 47]. We tested the VO<sub>2</sub>FITTING with data from a T400, usually used to prescribe the target swimming speed for aerobic power development, both in age-group and adult swimmers [14,48]. The workload demand during severe intensity exercise leads to a loss of muscle metabolic homeostasis that compromises the muscle power output, requiring additional motor unit recruitment and increased oxygen cost forming the  $\dot{V}O_{2sc}$  [49]. However, although the bi-exponential model was the best fit for 75% of the current sample when comparing with the mono-exponential model, the sum of squares residuals when fitting this model was smaller for all swimmers [13]. This contradiction may be explained by the inherent breath-by-breath noise observed in young swimmer's response profiles, which could mask any clear changes in ventilatory variables [45]. Nevertheless, even without significant differences observed between mono- and bi-exponential models for the remaining five swimmers, the mean A<sub>sc</sub> (2.5 and 5.9 mL·kg<sup>-1</sup>·min<sup>-1</sup> for mono- and bi-exponential, respectively), calculated as the difference between the  $\dot{V}O_2$  at the end and the amplitude of the primary phase, was  $\geq 2.1$  mL·kg<sup>-1</sup>·min<sup>-1</sup> (Fig 3). These data are suggestive of an imbalance in muscle metabolic homeostasis followed by peripheral fatigue [47, 49]. Thus, current data was consistent with the expected behaviour for the

exercise response in the severe intensity domain for most of the swimmers who performed the T400 [14, 50]. However, since both heavy and severe exercise may evince a slow component [13], concomitant analysis with other physiological variables and swimming technique could yield a complete overview of the swimmer profile [1].

Although VO<sub>2</sub>FITTING offers advantages, it is important to acknowledge some of the shortcomings and potential limitations of the software. First, although relevant for research and performance assessment, the off-transient  $\dot{V}O_2$  kinetics analysis is not yet available in this version. However, since VO<sub>2</sub>FITTING is open-source software, other mathematical functions traditionally used to estimate physiological parameters related to  $\dot{V}O_2$  kinetics can be incorporated into the software. Secondly, although VO<sub>2</sub>FITTING allows straightforward analysis of cardiorespiratory responses for research and performance in sports practitioners, it cannot be considered as the definitive solution for  $\dot{V}O_2$  kinetics data processing for novice/regular user because its interpretation requires knowledge about respiratory physiology. Although some commercial software provide intuitive graphical interfaces and relatively straightforward options to analyse  $\dot{V}O_2$  kinetics data, knowledge about respiratory physiology is also mandatory. Moreover, none of these commercial software are free or open-source. Thirdly, technical support and detailed user manuals of VO<sub>2</sub>FITTING (S1 File) are only available in English. Finally, despite the concurrent validity observed for all available models in VO<sub>2</sub>FITTING and examples illustrating its applicability, we have not examined constraints for parameter estimates, logistic and tri-exponential models. The future challenge includes the testing of all the remaining available options with experimental data and updating VO<sub>2</sub>FITTING documentation with examples to illustrate each of these available tools.

In conclusion, VO<sub>2</sub>FITTING has shown to be valid for characterising  $\dot{V}O_2$  kinetics in exercise. Initial concurrent validation showed perfect fits for all available models, with parameter estimates matching perfectly the known inputted values. The evaluation of severe intensity transitions in swimming has illustrated some applications and feasibilities of VO<sub>2</sub>FITTING. We identified the expected behaviour for severe intensity  $\dot{V}O_2$  kinetics for most swimmers, which, if assessed concurrently with other physiological variables and swimming technique analysis

should generate a complete (biophysical) overview of a swimmer's profile [1]. We also showed numerical fitting results when using supplementary swimming and running-related data (S1 File), illustrating other available options of VO<sub>2</sub>FITTING. This freely available software, which eases the  $\dot{V}O_2$  kinetics analysis in exercise, can be applied for research and performance in elite, sub-elite or recreational athletes. Since it is an open-source software, we believe that VO<sub>2</sub>FITTING has long-term utility for the sports science community.

### **Acknowledgments**

Authors acknowledge the support of clubs, coaches, swimmers and laboratory personnel involved in the current study.

### **Electronic Supplementary material**

**S1\_File** Supplementary material\_VO<sub>2</sub>FITTING Documentation

**S2\_File** Supplementary material\_Validation Datasets



## S1\_File (Electronic Supplementary material 1): VO<sub>2</sub>FITTING Documentation

### 1 VO<sub>2</sub>FITTING Tool

The VO<sub>2</sub>FITTING is a web application based on R language (R Core Team 2015), with support of the “Shiny” [1] package, that provides freely available software for characterizing  $\dot{V}O_2$  kinetics in exercise. The VO<sub>2</sub>FITTING software provides a dynamic and full analysis of the on-transient  $\dot{V}O_2$  responses to exercise, offering functionalities that confer enough flexibility to compare simultaneously several cardiodynamic responses with sufficient precision to meet researchers requirements.

### 2 Installation and quick tutorial

To run the software, the following configurations are necessary. VO<sub>2</sub>FITTING runs online inside a browser, therefore a Shiny server is required. This server can be configured for local access or shared access by multiple users. Details about the application, source code, installation instructions, and other documentation, can be verified on the landing page ([https://shiny.cespu.pt/vo2\\_news/](https://shiny.cespu.pt/vo2_news/)). Source code is released under a GPL3 license (<https://www.r-project.org/Licenses/GPL-3>). Likewise, an R environment should be available, where all the app dependencies are installed. The R command line (where VO<sub>2</sub>FITTING folder is located) is needed prior to each launch, using the following commands: *library(shiny)* and *runApp(vo2)*. In any of the cases above mentioned the following dependencies should be previously installed (Table 1):

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**Table 1.** Required Dependencies

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Library (shiny) [1]	#Version >= 0.14.2
Library (minpack.lm) [2]	#Version >= 1.2-0
Library (chron) [3]	#Version >= 2.3-47
Library (zoo) [4]	#Version >= 1.7-13
Library (bcrypt) [5]	#Version >= 0.2
Library (rmysql) [6]	#Version >= 0.11-3
Library (digest) [7]	#Version >= 0.6.10
Library (nlstools) [8]	#Version >= 1.0-2
Library (tseries) [9]	#Version >= 0.10-35
Library (openxlsx) [10]	#Version >= 3.0.0
Library (readods) [11]	#Version >= 1.6.4

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A local *MySQL* or *Mariadb* database server is also necessary. The database needs two tables named “Models” and “Users”, with the following structure, respectively (Table 2 and 3):

Field	Type	Null	Key	Default	Extra
id	mediumint (9)	No	PRI	Null	auto_increment
uid	mediumint(9)	No		Null	
modeltype	varchar(256)	No		Null	
modeldesc	varchar(512)	No		Null	
model	varchar(256)	No		Null	
data	varchar(256)	No		Null	
timestamp	char(25)	No		Null	

Field	Type	Null	Key	Default	Extra
id	mediumint(9)	No	PRI	Null	auto_increment
username	varchar(60)	Yes	UNI	Null	
password	char(60)	Yes		Null	

The dump *databasestructure.sql* can be imported if this structure cannot be created manually. Database encoding should be *utf8* and table collation *utf8\_general\_ci*. The database connection is configured in the file *db.ini*. Currently, there is no web interface to manage users. Thus, the small script *createuser.R* in the command line can be employed to create new users. The access to source code repository is granted upon request by email to the corresponding author.

### Quick tutorial

1. Click *browse* on the left of “Upload VO<sub>2</sub> data as a function of time” menu to upload a dataset (read section Input for help);
2. Choose *model* for fitting (or default);
3. Choose *VO<sub>2</sub> baseline* option.

### 3 Input

A text file must be used when setting the default input dataset, following the requirements below (See an example in Fig. 1):

1. The first line must have two different columns named by default *t* (time) and *VO<sub>2</sub>/kg*. They can be located in any position (1<sup>st</sup> and last columns, for example);
2. The expected time format (default) is hh:mm:ss;
3. The first data point from each column starts (by default) on the 4<sup>th</sup> line;
4. The expected *VO<sub>2</sub>/kg* units are mL·kg<sup>-1</sup>·min<sup>-1</sup>;

5. Columns are separated by default with semicolon;

However, the following options can be chosen at “Input and Models -> Data format” menu:

1. Other input formats, such as XLSX and ODS;
2. The sheet name where the data is located;
3. The line where the data starts;
4. The name of the column which contains time data;
5. The name of the column which contains  $\dot{V}O_2$  values;
6. The time format;
7. The data separator (text file format).

The Input file can have additional columns, which will be ignored. An example of an input dataset spreadsheet is shown in Fig. 1.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	t	Rf	VT	VE	VO2	VCO2	O2exp	CO2exp	VE/VO2	VE/VCO2	VO2/Kg	R	FeO2	FeCO2	HR
2	hh:mm:ss	b/min	l	l/min	ml/min	ml/min	ml	ml	---	---	ml/min/Kg	---	%	%	bpm
3															
4	00:01:10	10.91	1.55	16.90	504.79	527.09	267.73	58.95	33.48	32.06	7.21	1.04	17.28	3.81	99
5	00:01:12	26.55	0.86	22.80	747.97	725.81	145.85	33.35	30.48	31.41	10.69	0.97	16.98	3.88	99
6	00:01:13	42.86	1.30	55.60	1654.16	1571.41	225.30	44.77	33.61	35.38	23.63	0.95	17.37	3.45	98
7	00:01:15	25.97	1.41	36.74	1189.96	1150.77	241.01	54.06	30.88	31.93	17.00	0.97	17.04	3.82	96
8	00:01:17	38.22	1.08	41.08	1386.71	1361.52	181.24	43.45	29.63	30.17	19.81	0.98	16.86	4.04	97
9	00:01:19	27.52	1.45	39.97	1205.87	1177.40	251.21	52.22	33.15	33.95	17.23	0.98	17.30	3.60	101
10	00:01:21	39.74	1.99	79.07	2750.89	2635.27	333.41	80.88	28.74	30.00	39.30	0.96	16.76	4.06	108
11	00:01:22	38.22	1.74	66.42	2097.76	1928.36	298.43	61.60	31.66	34.44	29.97	0.92	17.17	3.54	113
12	00:01:24	41.67	1.18	49.30	1505.59	1388.51	204.60	40.70	32.74	35.50	21.51	0.92	17.29	3.44	114
13	00:01:26	29.27	1.42	41.58	1266.26	1161.03	245.90	48.45	32.84	35.82	18.09	0.92	17.31	3.41	125
14	00:01:27	38.22	1.88	71.72	2778.20	2290.80	308.02	73.13	25.82	31.31	39.69	0.82	16.41	3.90	132
15	00:01:29	33.33	2.08	69.46	2779.10	2181.69	339.74	79.86	24.99	31.84	39.70	0.79	16.30	3.83	145
16	00:01:31	37.50	1.83	68.77	2812.72	2178.69	297.31	70.88	24.45	31.56	40.18	0.77	16.21	3.87	157
17	00:01:33	25.86	2.00	51.83	2255.67	1741.13	318.93	82.10	22.98	29.77	32.22	0.77	15.91	4.10	177
18	00:01:35	35.71	1.96	69.87	3246.66	2404.80	305.37	82.10	21.52	29.05	46.38	0.74	15.61	4.20	174
19	00:01:36	37.97	1.99	75.45	3571.74	2575.88	308.63	82.72	21.12	29.29	51.02	0.72	15.53	4.16	175
20	00:01:38	36.81	2.05	75.31	3476.36	2567.67	320.16	85.06	21.66	29.33	49.66	0.74	15.65	4.16	176
21	00:01:40	34.88	2.13	74.32	3187.87	2382.64	341.17	83.33	23.31	31.19	45.54	0.75	16.01	3.91	174

Fig. 1. Example of input dataset

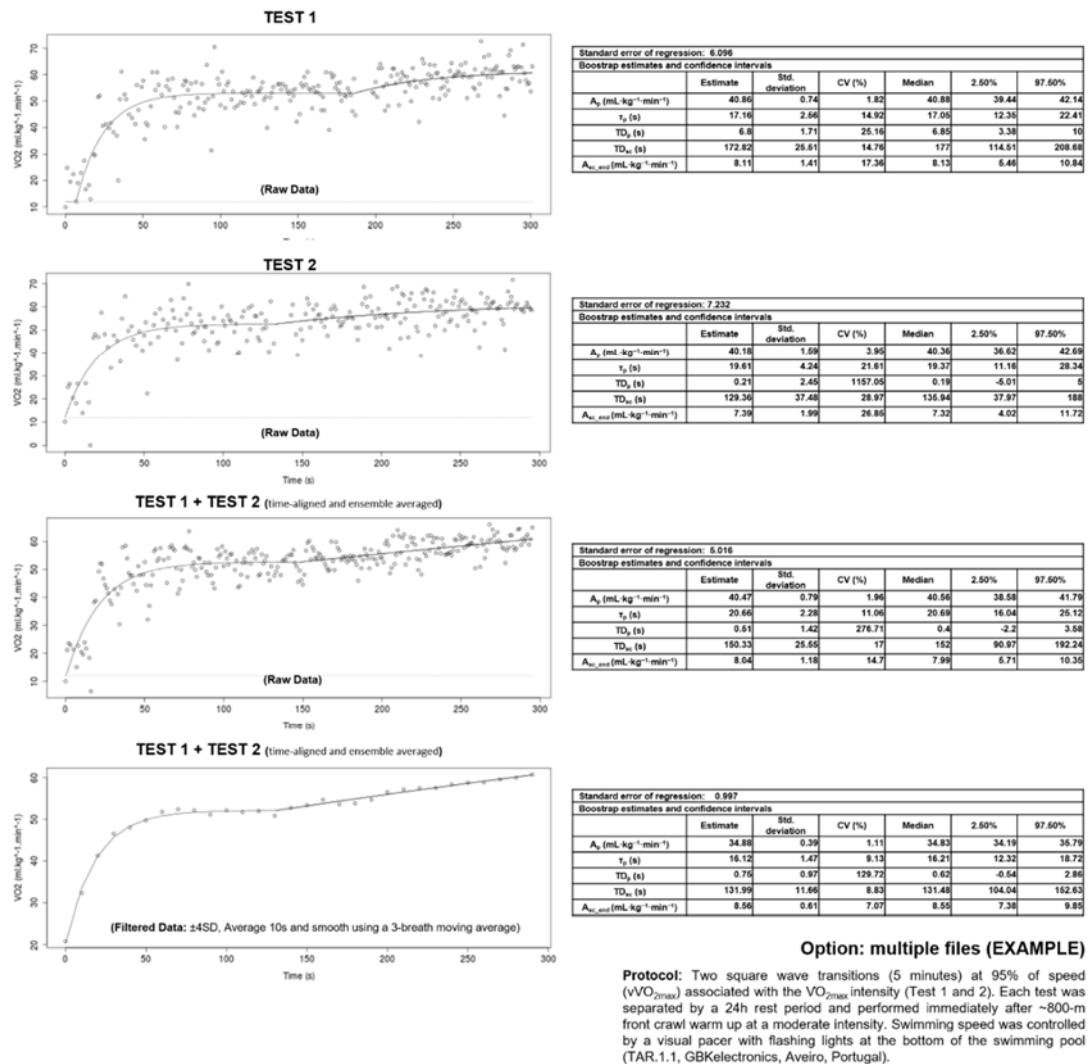
*Option: multiple files*

If two or more observations need to be time-aligned to yield a single profile, VO<sub>2</sub>FITTING has the option to upload multiple files and combine them in one. It is necessary to hold the CTRL button while selecting those files. There are three options to combine the datasets: using median, average or joining all data. By selecting median, if the instant  $t=1s$  has three observations, VO<sub>2</sub>FITTING will calculate the median for those three observations. The recommended (and the default) option is median, since is less sensitive to outliers. VO<sub>2</sub>FITTING starts

by creating a list of all the times when the sampling times are not identical in all the files, as the following example:

If: Times file 1= 1s,3s,7s and Times file 2= 1s,2s,7s; Thus, all Times: 1s,2s,3s,7s

Before combining the  $\dot{V}O_2$  data,  $VO_2$ FITTING needs information for  $\dot{V}O_2$  in file 1 for  $t=2s$ , and in file 2 for  $t=3s$ .  $VO_2$ FITTING uses linear interpolation to find that information. For instance, in the case of  $\dot{V}O_2$  for file 1 at  $t=2s$ ,  $VO_2$ FITTING will linearly interpolate from  $t=1s$ , to  $t=3s$  to estimate what the  $\dot{V}O_2$  observation would be at  $t=2s$ . An example of two time-aligned tests is shown in Fig. 2, where one swimmer performed two square wave transitions (5 minutes) at 95% of velocity ( $v\dot{V}O_{2max}$ ) associated with the  $\dot{V}O_{2max}$  intensity, separated by a 24 h rest period and performed immediately after ~800-m front crawl warm-up at a moderate intensity. Swimming speed was controlled by a visual pacer with flashing lights at the bottom of the swimming pool (TAR.1.1, GBKelectronics, Aveiro, Portugal).



**Fig. 2** Example of two time-aligned tests with *multiple files* option on VO<sub>2</sub>FITTING. From the top to the bottom plots: Test 1 with raw data, Test 2 with raw data, Test 1 and 2 time-aligned with raw data and filtered data.

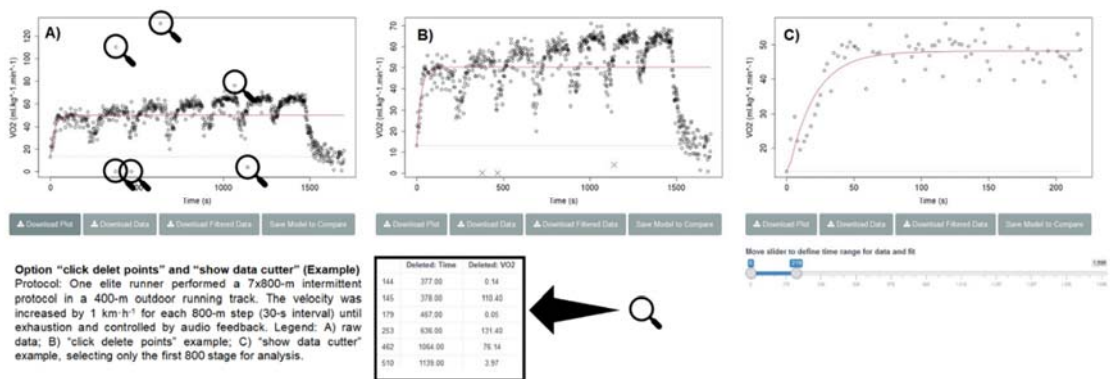
**Option: click delete points**

This option allows to click on each point, deleting them if necessary. Thus, selected points are removed and not considered for modelling. Soon after, VO<sub>2</sub>FITTING adjusts the fit automatically. By clicking in the same point again or unchecking this option, it is possible to reset it.

**Option: show data cutter**

A slider will appear below the plotted graphic when selecting this option. The slider allows to restrict the model fitting in a specific time range.

Fig. 3 shows examples for *click delete points* and *data cutter* options using a data set obtained from one elite runner during an 7x800-m intermittent protocol performed on a 400-m outdoor running track. The velocity was increased by 1 km·h<sup>-1</sup> for each 800-m step with a 30-s rest interval until exhaustion and controlled by audio feedback emitted in markers placed at 100-m intervals.



**Fig. 3.** Illustration of *click delete points* and *show data cutter* options. Data from a square wave transition performed in treadmill by an Elite runner.

*Option: multiply by mass*

This option can be used to change  $\dot{V}O_2$  dataset *unit of measurement* to ml·min<sup>-1</sup>.

*Option: choose how to define  $vo_{2baseline}$*

Adjusted by fitting (manual)

This option will fit the  $\dot{V}O_{2baseline}$  automatically, limiting the lower/upper range of the parameter for fitting to manually set values. Starting value will be calculated as the middle of the range.

Adjusted by fitting (automatic)

This option can be used to fit  $\dot{V}O_{2baseline}$  automatically, ranging from 0 to +Inf, with a starting value of 40 (not really meaningful).

Manual Value

By selecting this option, the  $\dot{V}O_{2baseline}$  can be introduced manually, usually in units of mL·kg<sup>-1</sup>·min<sup>-1</sup>. If the "Multiply by mass" option has been chosen, then  $\dot{V}O_{2baseline}$  in mL·min<sup>-1</sup> can be introduced.

#### Manual Value backwards repetition

This option can be useful if input data has  $\dot{V}O_2$  values that starts from the beginning of the exercise ( $t=0$ ), but  $\dot{V}O_{2baseline}$  is in another data file. This is one option to fit the onset of the first exponential by creating artificial baseline data, so the time delay can be accurately determined.

#### Average/Median of first X points

By setting this option, there is no limit for the number of points to define  $\dot{V}O_{2baseline}$ .

#### First data point

By selecting this option, the first  $\dot{V}O_2$  data point can be defined as the  $\dot{V}O_{2baseline}$  value.

### **4 Filtering**

It is arguable whether the model fitting should be conducted with filtered or raw data, since more stringency (allowing more 'errant' data points) could exert a major influence on parameter estimation. However, all filters mentioned below are available on  $VO_2FITTING$  and can be applied before fitting the model and by the order which are selected.

#### *Moving average*

Simple moving average using R's filter function. The number of points when using this option can be specified in the interface. An odd number of points is recommended.

#### *Moving median*

Simple moving median using R's runmed function. The number of points when using this option can be specified in the interface. An odd number of points is required.

### *Interpolate every 1s*

This filter will fill gaps using linear interpolation every 1s. For example, in one file with data points: (t=1s,  $\dot{V}O_2=30$ ) (t=4s,  $\dot{V}O_2=40$ ), VO<sub>2</sub>FITTING will create new data points at t=2s and t=3s.

### *Averaging in a box*

By selecting this filter, VO<sub>2</sub>FITTING will create boxes of the specified number of seconds and average all the data in that box.

For example, consider the data:

- t=101s,  $\dot{V}O_2=30$
- t=102s,  $\dot{V}O_2=40$
- t=103s,  $\dot{V}O_2=50$
- t=104s,  $\dot{V}O_2=60$

By selecting *averaging in a box* is a box of 2 seconds, the new data will be:

- t=101.5s,  $\dot{V}O_2=35$
- t=103.5s,  $\dot{V}O_2=55$

(Note: this exact behavior is still being worked on.)

### *Rolling standard deviation*

Using an odd number of points, this filter calculates rolling mean and rolling standard deviation, excluding points which are above or below local mean  $\pm$  threshold $\times$ std. deviation. For better results, an option which calculates the median of all rolling std. deviations is available and active by default. This median is then used as the reference std. deviation, rather than the local std. deviation. The number of points and the threshold can be chosen, which by default is 4. The exclusion of these aberrant values ( $> 4$  standard deviations about the local mean) of  $\dot{V}O_2$  is justified by the fact that they typically arise due to swallowing or coughing, or some other reason unrelated to the physiological response of interest [12, 14]. It is important to note that for a width of 3, one point is removed in the beginning and in the end. For a width of 5, two points are removed and so on. Data with few points in the beginning might be a problem for fitting  $\dot{V}O_2$  kinetics.



Table 4, Table 5 and Fig. 4 illustrate quantitatively and graphically the use of selected filters in different mathematical models with datasets from swimming (n=1; adult) and running (N=1; adult), particularly  $\dot{V}O_2$  related parameters and fits obtained from mono- and bi-exponential models (raw and filtered data) during square wave transitions at 100% of speed ( $v\dot{V}O_{2max}$ ) associated with the  $\dot{V}O_{2max}$  intensity.

**Table 4.** Estimated  $\dot{V}O_2$  related parameters obtained from a mono-exponential model from running (n=1) and swimming (n=1) during a square wave transition at 100% of  $v\dot{V}O_{2max}$ , using raw and filtered data ( $\pm 4SD$ , average 10s and smooth by a 3-breath moving average)

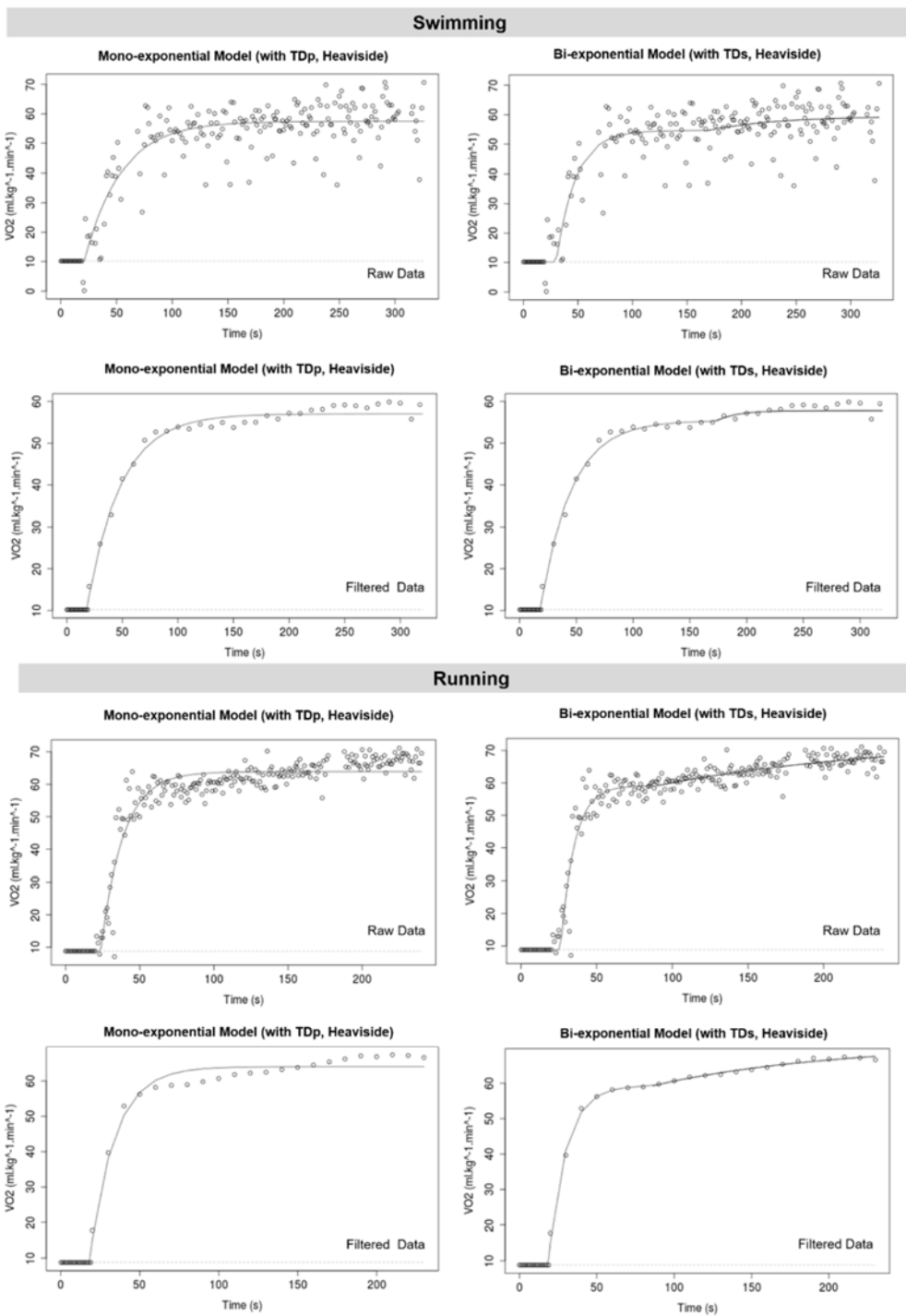
	Raw		Filtered	
	Bi-exponential Swimming (N=1)	Bi-exponential Running (N=1)	Bi-exponential Swimming (N=1)	Bi-exponential Running (N=1)
$A_0$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	10.2	8.8	10.2	8.8
$A_p$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	47.3	55.1	46.84	55.2
CV (%)	1.4%	0.6%	0.8%	0.8%
$TD_p$ (s)	20.9	23.6	17.8	18.0
CV (%)	12.0%	2.6%	4.3%	2.2%
$\tau_p$ (s)	32.9	15.1	30.4	15.8
CV (%)	12.3%	6.4%	5.6%	7.0%
$A_{sc\_end}$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	-	-	-	-
CV (%)	-	-	-	-
$TD_{sc}$ (s)	-	-	-	-
CV (%)	-	-	-	-
$\tau_{sc}$ (s)	-	-	-	-
CV (%)	-	-	-	-
$\dot{V}O_2$ at the end (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	58.8	67.2	57.4	66.7
$v\dot{V}O_2$ max (m.s <sup>-1</sup> )	1.38	5.10	1.38	5.10
Time limit at $v\dot{V}O_2$ max (s)	259	220	259	220

$A_0$  is the  $\dot{V}O_2$  at rest;  $A_p$  and  $A_{sc\_end}$ ,  $TD_p$  and  $TD_{sc}$ , and  $\tau_p$  and  $\tau_{sc}$  are respectively amplitudes, corresponding time delays and time constants of the fast and slow  $\dot{V}O_2$  components. CV (%) is the coefficient of variation for each parameter estimate.

**Table 5.** Estimated  $\dot{V}O_2$  related parameters obtained from a bi-exponential model from running (n=1) and swimming (n=1) during a square wave transition at 100% of  $v\dot{V}O_{2max}$ , using raw and filtered data ( $\pm 4SD$ , average 10s and smooth by a 3-breath moving average)

	Raw		Filtered	
	Bi-exponential Swimming (N=1)	Bi-exponential Running (N=1)	Bi-exponential Swimming (N=1)	Bi-exponential Running (N=1)
$A_0$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	10.2	8.8	10.2	8.8
$A_p$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	43.4	50.0	42.7	50.2
CV (%)	4.7%	3.6%	8.9%	2.5%
$TD_p$ (s)	29.8	26.1	18.2	18.52
CV (%)	10.3%	2.5%	4.9%	0.8%
$\tau_p$ (s)	17.7	8.9	26.0	11.2
CV (%)	26.2%	13.6%	18.6%	6.0%
$A_{sc\_end}$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	5.9	9.4	5.3	8.6
CV (%)	39.7%	16.44%	72.5%	16.6%
$TD_{sc}$ (s)	131.7	82.9	81.4	81.9
CV (%)	55.8%	29.18%	86.9%	27.9%
$\tau_{sc}$ (s)	10108	29854	17498	6587
CV (%)	765%	460%	713%	995%
$\dot{V}O_2$ at the end (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	58.8	67.2	57.4	66.7
$v\dot{V}O_2$ max (m.s <sup>-1</sup> )	1.38	5.10	1.38	5.10
Time limit at $v\dot{V}O_2$ max (s)	259	220	259	220

$A_0$  is the  $\dot{V}O_2$  at rest;  $A_p$  and  $A_{sc\_end}$ ,  $TD_p$  and  $TD_{sc}$ , and  $\tau_p$  and  $\tau_{sc}$  are respectively amplitudes, corresponding time delays and time constants of the fast and slow  $\dot{V}O_2$  components. CV (%) is the coefficient of variation for each parameter estimate.



**FILTERING (EXAMPLE)**

Protocol: Square wave transition at 100% of speed ( $\dot{V}O_{2max}$ ) associated with the  $\dot{V}O_{2max}$  intensity, performed by one swimmer and one runner immediately after 5 min warm-up exercise at moderate intensity. Swimming and running speed were controlled by a visual pacer with flashing lights.

**Fig. 4.** Example of  $\dot{V}O_2$  fits obtained from a mono- and bi-exponential models from running (n=1) and swimming (n=1) during a square wave transition at 100% of  $\dot{V}O_{2max}$ , using raw and filtered data ( $\pm 4SD$ , average 10s and smooth by a 3-breath moving average)

## 5 Available models

Find below the available models:

### *Mono-exponential (no TDp)*

There is no time delay in this model, so it is assumed that the exponential starts nearly or on the first data point.

$$\dot{V}O_{2\text{baseline}} + A_P \left( 1 - e^{-\frac{t}{T_P}} \right) \quad (1)$$

### *Mono-exponential (with TDp, Heaviside)*

The first 20 s of data after the onset of exercise (cardiodynamic phase) is not considered for  $\dot{V}O_2$  kinetics analysis in this model. This model also includes the Heaviside step function [13].

Given the Heaviside step function:

$$H(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases} \quad (2)$$

The model consists of a mono-exponential, with the onset only after TDp (Time delay of primary phase):

$$\dot{V}O_{2\text{baseline}} + H(t - TD_p) A_P \left( 1 - e^{-\frac{t - TD_p}{T_P}} \right) \quad (3)$$

### *Bi-exponential (with TDs, Heaviside)*

This is bi-exponential model with flexible time delays for the onset of each exponential. The first 20-s of data after the onset of exercise (cardiodynamic phase) are not considered for  $\dot{V}O_2$  kinetics analysis in this model. This model also includes the Heaviside step function for both exponentials [13]. The model consists of two exponentials, where the first one only starts effectively after TDp (time delay of primary phase) and the second after TDsc (time delay of slow component):

$$\dot{V}O_{2\text{baseline}} + H(t - TD_p) A_P \left( 1 - e^{-\frac{t - TD_p}{T_P}} \right) + H(t - TD_{sc}) A_{sc} \left( 1 - e^{-\frac{t - TD_{sc}}{T_{sc}}} \right) \quad (4)$$

### *Bi-exponential (no TDp, Heaviside)*

The model consists of two exponentials, the first one starts immediately, and the other after TDsc. This model includes Heaviside step functions [13] for the second exponential:

$$\dot{V}O_{2\text{baseline}} + A_P \left(1 - e^{-\frac{t}{T_p}}\right) + H(t - TD_{sc}) A_{sc} \left(1 - e^{-\frac{t - TD_{sc}}{T_{sc}}}\right) \quad (5)$$

*Mono-exponential and linear slow comp. (Heaviside)*

This model is similar to previous one (Bi-exponential, with TDs, Heaviside), but rather than considering the onset of a second exponential, the onset of a linear function is considered:

$$\dot{V}O_{2\text{baseline}} + H(t - TD_p) A_P \left(1 - e^{-\frac{t - TD_p}{T_p}}\right) + H(t - TD_{sc}) T_{sc} (t - TD_{sc}) \quad (6)$$

*Logistic Model*

This experimental model was included for those situations where  $\dot{V}O_2$  profile is similar to a logistic function:

$$\dot{V}O_{2\text{baseline}} + (A_P - \dot{V}O_{2\text{baseline}}) / \left(1 + e^{-\frac{T_{\text{mid}} - t}{T_p}}\right) \quad (7)$$

*Tri-exponential (Heaviside)*

Although there are a few studies using tri-exponential models, it is also available, with onsets at TD<sub>cd</sub> (cardiodynamic phase), TD<sub>p</sub> and TD<sub>sc</sub>:

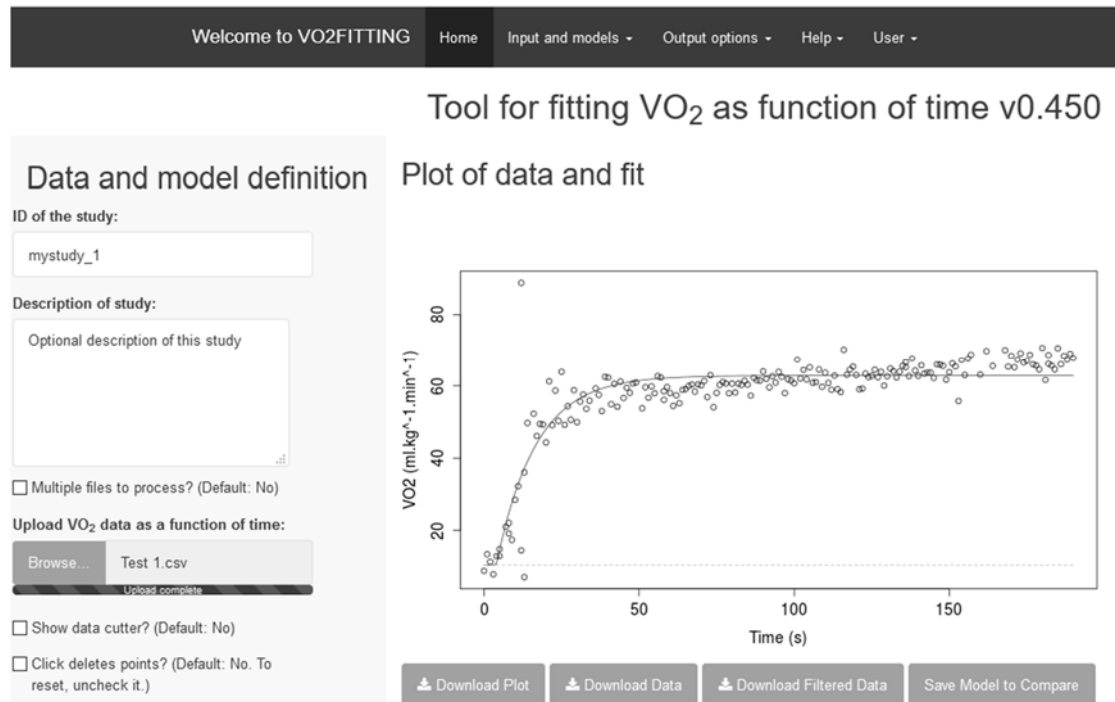
$$\dot{V}O_{2\text{baseline}} + H(t - TD_{cd}) A_{cd} \left(1 - e^{-\frac{t - TD_{cd}}{T_{cd}}}\right) + H(t - TD_p) A_P \left(1 - e^{-\frac{t - TD_p}{T_p}}\right) + H(t - TD_{sc}) A_{sc} \left(1 - e^{-\frac{t - TD_{sc}}{T_{sc}}}\right) \quad (8)$$

## 6 Output

*Main output window*

Plot of data and fit

- By clicking anywhere in the plot, the coordinates of the nearest time (s) and  $\dot{V}O_2$  data point appear.
- By clicking *download Data* or “Download Filtered Data”, time (s) and  $\dot{V}O_2$  in CSV format can be downloaded, with all the remaining columns might ignored. The *ID of the study* (defined in the interface) determines the name of the file. *Description of the study* will be affixed to the end of the file.
- By clicking *Save Model to Compare*, after logging in, a dialog will appear asking for a small description of the model to make it easier to identify it later while comparing models in the “Input and models -> Show saved models” section. After clicking *OK* the data and the current model are saved in the database together with the small description.



**Fig. 5** Main output window (Plot of data and fit)

### Fitting Results

- The first table(s) list(s) shows: estimate of the fitted parameters, standard error, t-value and a two-sided p-value for the null/alternative hypothesis “H0 - the parameter is zero/Ha - the parameter is significantly different from zero”, i.e., “this parameter contributes to the explanatory power of the model” (if p-value less than the significance level, defined a priori). In *Output Options* -> *Auxiliary Reports* shows confidence intervals for the parameter estimates using profile likelihood (stable if data is not noisy).
- $\dot{V}O_{2\text{baseline}}$  and mean  $\dot{V}O_2$  data in the last 30 and 60 seconds (using raw and filtered data) are shown next to this table;
- By selecting the option “*Show bootstrap confidence intervals*” in *Output Options* -> *Auxiliary reports*, bootstrap estimates of the parameters will be calculated (This option can slow the application). There is no limit for the number of bootstrap samples (by default: 1000). The routine is based on the code from *nlstools* package [15].
- By selecting the option *Show a table of the 5 points where  $\dot{V}O_2$  is higher* in *Output Options* -> *Auxiliary reports*, a table of the 5 points where the  $\dot{V}O_2$  is higher (with and without subtraction of  $\dot{V}O_{2\text{baseline}}$ ) with raw and filtered data is shown.

- By selecting the option *Show:  $\dot{V}O_2$  mean (30s and 60s) -  $A_p$*  in *Output Options - > Auxiliary reports*, a table of the average of the  $\dot{V}O_2$  in the last 30s and 60s with the fitted fast component amplitude ( $A_p$ ) subtracted is also shown, using raw and filtered data. This option is useful for some intensity domains where the asymptotic value of the second function is not necessarily reached at the end of the exercise.
  - By selecting the option *Calculate and show CV for the last 30s and 60s* in *Output options -> Auxiliary reports*, a table with the coefficients of variation for the last 30s and 60s of the data is also shown (raw and filtered data).
  - By selecting the option *Calculate and show slow component rigid intervals*, a table of the mean of  $\dot{V}O_2$  in the end of the data (the number of seconds to average out can be specified) less the average of  $\dot{V}O_2$  at specific time intervals is shown, as well as the mean of those differences and standard deviations. When: (1) upload data with initial rest; (2) choosing  *$\dot{V}O_{2baseline}$  manual value with backwards repetition*; it is possible to define where the exercise starts in seconds for the rigid intervals to make sense. Thus, when, for example 100 to 120 s in the output, it means time in seconds. Note: it is possible to input negative values.
- $\dot{V}O_{2end} - \dot{V}O_2$  (100\_to\_120) s;
  - $\dot{V}O_{2end} - \dot{V}O_2$  (90\_to\_120) s;
  - $\dot{V}O_{2end} - \dot{V}O_2$  (80\_to\_120) s;
  - $\dot{V}O_{2end} - \dot{V}O_2$  (lower and upper limits you may define in the interface) s.

### Plots of residuals

The plots of residuals permits evaluation of the goodness-of-fit of the model.

Several plots are shown by default:

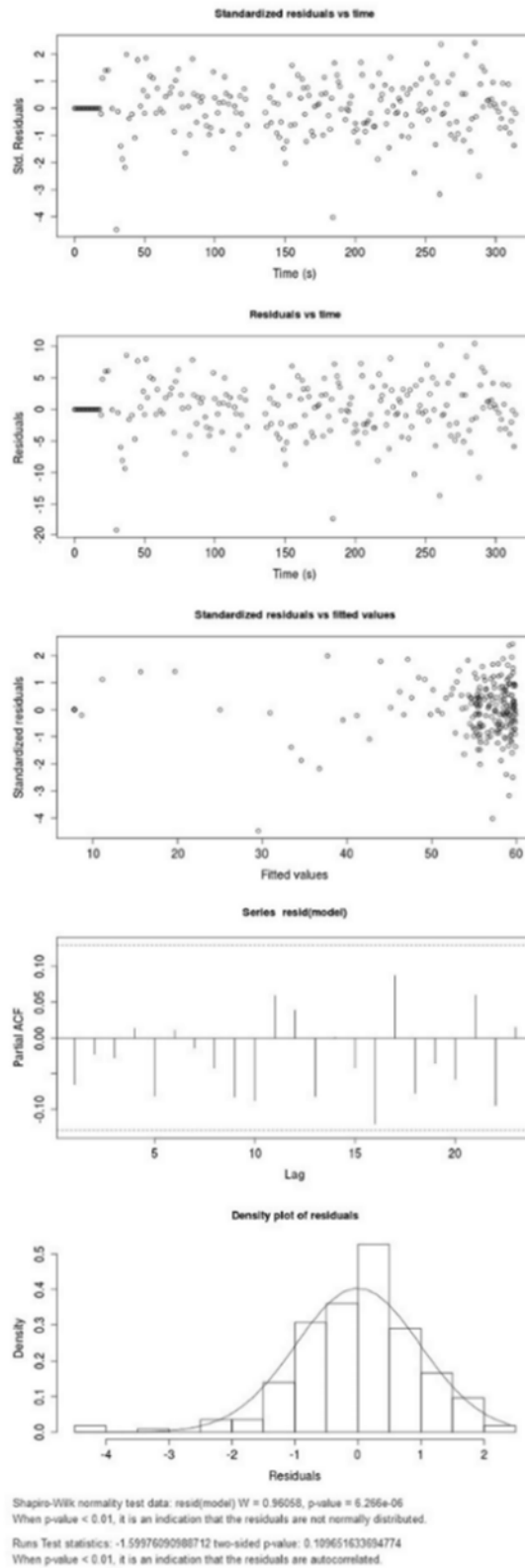
- Standardized residuals vs time;
- Residuals vs time;
- Standardized residuals vs fitted values;
- Partial autocorrelation function as a function of lag;
- Histogram of residuals with a Gaussian distribution on top of it;

The following statistical analysis are available after the plots of the residuals:

- *the output of a Shapiro-Wilk test on the residuals.* If the p-value of the test is below the significance level that was defined a priori, it is an indication that the residuals are probably not normally distributed.
- *the simple run test output.* If the p-value of the test is below the significance level that was defined a priori, it is an indication that the residuals are probably autocorrelated.

Fig. 6 shows a screenshot from the bottom of the VO<sub>2</sub>FITTING home menu detailing residuals plots to evaluate the goodness of fit of the T400 modelled (swimming)  $\dot{V}O_2$  response (bi-exponential) of the same swimmer presented in Fig. 2 of the main manuscript.





**Fig. 6** Residuals plots from a T400 (swimming) modelled  $\dot{V}O_2$  response (bi-exponential). From the top to the bottom: *Standardized residuals and residuals vs time*, *standardized residuals vs fitted values*, partial autocorrelation function as a function of lag, histogram of residuals with a Gaussian distribution, output of a Shapiro-Wilk test on the residuals and the output of a simple test are shown.

## Confidence Regions - Contours based on RSS

- By selecting the option *Show contours based on the residual sum of squares* in *Output Options -> Auxiliary reports*, contours based on RSS will be available (this option can also slow the application). Expansion factor of the parameter intervals defining the grids can be selected. The factor can be increased if the 95 percent Beale's confidence regions exceed the plot size and a better view is desired. The routine is based on the code from *nlstools* package [15].

## 7 Constraining parameters in curve fitting

There is a functionality which allows individual constraining parameters (to setting the limits). These parameter procedures are located in the home menu, as shown in Fig. 7:

**Model initial parameters**

Using model

$$VO_{2baseline} + H(t - TD_p)A_p(1 - e^{-(t-TD_p)/\tau_p})$$

Initial  $A_p$  min: 0

Initial  $A_p$  max: 100

Constraint  $A_p$ ?

Initial  $\tau_p$  min: 0.1

Initial  $\tau_p$  max: 15

Constraint  $\tau_p$ ?

Initial  $TD_p$  min: -20

Initial  $TD_p$  max: 20

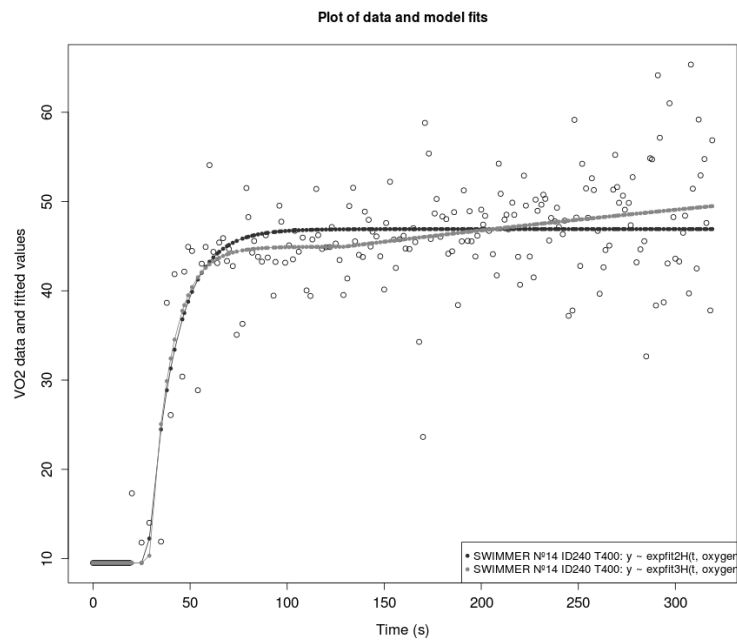
Constraint  $TD_p$ ?

Unconstrain all

**Fig 7.** Constraining parameters window for Mono-exponential with TDp, Heaviside) curve fitting.

## 8 Model comparisons

By selecting the option *Show Saved Models* in *Input Models* -> *Show Saved Models*, a list of saved fits is shown. By selecting the models to compare and clicking in *Compare Models*, a plot with the fit of all compared models will be shown (see Fig. 8). It is important to observe the order which each model is selected. The first selected model defines the corresponding base data points to be shown. A legend is automatically added. To better understand the functions used in the modelling, check the beginning of the file helpers.R. It is possible to select up to 21 saved models to compare at the same time, or only one for individual visual analysis.



**Fig. 8.** Example of model comparison between two saved fits.

The currently available option to compare each model is ANOVA, in which comparison analysis will be displayed above the plot. It is up to the user to check if the analysis makes sense or not, which will depend on the models chosen for comparison.

## 9 Known issues and future work

<https://gitlab.com/vo2fitting/app/issues>



## Chapter 4

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### Effects of detraining in age-group swimmers performance, energetics and technique

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Submitted to Journal of Sports Sciences

## Abstract

Changes in performance, energetics and technique during age-group swimmers off-season inform the prescription of training for the following season. Age-group swimmers ( $n=15$ , age  $14.3\pm 0.7$  y) of equal maturational stage performed a 400-m front crawl (T400) before and after a four-weeks training cessation period. Performance-related physiological and biomechanical variables were obtained controlling for anthropometric and non-swimming specific physical activities during off-season. T400 time decreased 3.8% (95%CI 1.4 to 6.1%;  $p<0.01$ ;  $d=0.90$ ) with non-specific physical activities ( $1814\pm 1989$  MET-min $\cdot$ wk $^{-1}$ ) accounting for ~40% of the underlying variance ( $p=0.01$ ;  $\eta^2=0.40$ ). Stroke rate and stroke index decreased despite similar stroke length and index of coordination values. Although mean response time, amplitude, maximal oxygen uptake, heart rate, total energy expenditure and energy cost were similar, aerobic contribution decreased ~1.8% (-2.7 to -0.9%;  $p<0.01$ ;  $d=-1.19$ ) and anaerobic lactic contribution increased ~1.6% (0.8 to 2.5%;  $p<0.01$ ;  $d=1.08$ ). Impaired performance was mainly associated with a decreased stroke rate ( $r=-0.85$  to  $-0.61$ ;  $p\leq 0.02$ ), increased peak blood lactate ( $r=-0.52$ ;  $p=0.05$ ) and non-swimming specific physical activities performed during the off-season ( $r=-0.58$ ;  $p=0.03$ ). The end-of-season cessation of training yielded moderate impairments in age-group swimmers performance-related physiological and biomechanical factors, however non-specific physical activities can minimise fitness losses.

**Keywords:** Swimming · Age-Group · Off-Season · Training Cessation · Detraining

## Introduction

Tracking physiological and biomechanical changes associated with performance provides important insights into swimmers preparation, but detailed information on parallel changes in swimming performance are difficult to obtain in the aquatic environment (Ayabakan et al., 2006; Csajagi, Szauder, Major, & Pavlik, 2015; Morais, Marques, Marinho, Silva, & Barbosa, 2014). Swimming-related studies are mostly cross-sectional in approach and, although relevant, they do not provide conclusive information about cause-and-effect relationships between swimming determinant variables and performance during training and off-season phases. Therefore, longitudinal data on swimmers training is still required.

The partial or complete loss of training-induced anatomical, physiological and functional adaptations with reduced training, or even training cessation, is termed detraining (Mujika & Padilla, 2000). Detraining can be caused by illness, injury or, more commonly, the post-season break. Typically, a four-weeks off-season is applied for high-level swimmers, a period used in detraining-related studies (Mujika & Padilla, 2000). Age-group swimmers typically recover for four- to six-weeks in the off-season, but this duration may differ according to the calendar of each national swimming federation (Garrido et al., 2010). In contrast to most senior swimmers, young swimmers usually enjoy the off-season with complete cessation of training. Although coaches often report reductions in fitness and loss of technique, evidence-based outcomes on the effects of detraining in young adolescent swimmers are scarce. Likewise, training reduction is important for performance improvements, but the effects of the duration of training cessation and its impact on performance are not well reported for age-group swimmers. It is also unclear the extent to which critical physiological and biomechanical characteristics can change during the off-season.

Longitudinal studies on physiological and morphological changes in age-group swimmers indicate that performance improvements are dependent on growth and training stimuli (Ayabakan et al., 2006; Csajagi et al., 2015; Kavouras & Troup, 1996). Likewise, gender differences and intra-individual variability for performance-related biomechanical factors have been described over two competitive seasons (Barbosa et al., 2015; Morais et al., 2014). However, physiological and biomechanical adaptations are transitory, and might decline

when training load is reduced after the main competition of the season. This explains why some coaches encourage age-group swimmers to undertake non-swimming specific physical activities (like dry land sports, cross-training or gym-based exercises) during the off-season. However, the effects of these land physical activities need to be quantified, since they may offset the detraining related to swimming training. For instance, Garrido et al. (2010) indicated that strength remained stable and 25- and 50-m swimming performance improved after six-weeks of training cessation in 12 years old age-group swimmers, but the effects of growth and non-specific physical activities performed during that period were not controlled.

Performance during a swimming event depends on the conversion of metabolic into mechanical power through a given energetic efficiency (Barbosa et al., 2010; Figueiredo, Pendergast, et al., 2013). The total energy expenditure ( $E_{tot}$ ), defined as the sum of aerobic (Aer), anaerobic lactic (AnL) and anaerobic alactic (AnAL) energy contributions during different events, and the energy cost (C; the energy consumed to cover one unit of distance while swimming at a given speed), have been well studied through indirect calorimetry (see also Sousa, Figueiredo, Zamparo, Vilas-Boas, & Fernandes, 2013). Detraining during the off-season may increase the oxygen uptake ( $\dot{V}O_2$ ) and blood lactate concentrations ( $[La^-]$ ) for a given effort, making harder to sustain the swimming speeds ( $v$ ) reached at the end of the previous season. Maximal oxygen uptake ( $\dot{V}O_{2max}$ ) is a relevant physiological parameter of aerobic function in swimming and analysis of the dynamic  $\dot{V}O_2$  response following the onset of exercise ( $\dot{V}O_2$  kinetics) can provide a more detailed picture of its cardiorespiratory determinants (Ribeiro et al., 2017). To date no study has yet quantified the effects of detraining on  $\dot{V}O_2$  kinetics after the off-season in age-group swimmers. It is plausible that this pause may also influence  $\dot{V}O_2$  related parameters and the subsequent progression of adolescent swimmers.

Age-group swimmers technique is also influenced by training that underpins improvements in swimming performance over a training season (Morais et al., 2014). Improvements in swimming biomechanics after ~10-weeks of off-season in age-group swimmers were largely explained by anthropometric changes related to growth (Moreira et al., 2014), but, again, the effects of non-swimming



specific physical activity were not controlled. Thus, growth and non-swimming physical activities effects should be accounted when assessing performance changes through prospective detraining studies, since they could reduce, at least in part, the loss of swimming-specific fitness during the transition to the next competitive season (Neufer, 1989). The aim of the study was to assess the performance, physiological and biomechanical effects of a typical off-season period in age-group swimmers. The anthropometric growth and non-swimming specific physical activities performed during this period of swimming training cessation were controlled. We expected that training cessation at the end of a training season would yield impairments in performance, energetics and technical variables, partially offset by a swimmer's growth and non-specific physical activities during the transition period.

## **Methods**

### ***Experimental Approach to the Problem***

A longitudinal single cohort study was conducted, and swimmers were tested before and after a four-weeks off-season period. Repeated measures of performance-related physiological and biomechanical variables, controlling for anthropometric and non-swimming specific physical activities, were obtained. The first experimental testing (PRE) took place immediately after the most important competition of the year at the end of the training season. Swimmers were then instructed to refrain from swimming-pool training during the whole off-season. The second experimental testing (POST) was conducted four-weeks later, during the first week of the new training season.

Anthropometric variables and pubertal maturation stage were assessed in both testing sessions and self-reported physical activity data from the off-season was obtained in the POST evaluation. The experimental protocol took place in a 25-m indoor pool with 27.5 and 25.9°C of water and air temperatures (respectively) and 65% relative humidity. After an ~800-m moderate intensity front crawl warm-up, swimmers performed a 400-m maximal effort front crawl swim test (T400) for performance, physiological and biomechanical measurements. The T400 was chosen given its validity and feasibility for assessing aerobic power in age-group swimmers (Laffite et al., 2004; Zacca et al., 2017). All participants avoided

vigorous exercise in the previous 24 h, were well-hydrated, abstained from caffeine for, at least, 3 h before testing and encouraged verbally during the T400.

### **Participants**

Fifteen late to post pubertal age-group swimmers, six boys and nine girls ( $14.5 \pm 0.8$  and  $14.2 \pm 0.6$  y, respectively), volunteered to participate in the current study. Swimmers had over 5 y of competitive experience and trained six to seven swimming sessions per week in the same squad and under direction of the same coach. Table 1 summarizes the in-water training volumes for each intensity training zone (adapted from Mujika et al., 1995) over the last 16-weeks macrocycle immediately before the off-season. The training season was 48-weeks long, divided in three major macrocycles, as proposed for school-age swimmers (Tschien, 1977). Swimmers parents were informed about the benefits and risks of participating in the current study prior to signing an informed consent form, which was approved by the ethics board of the local university and performed according to the Helsinki Declaration.

**Table 1.** In-water training volumes per training zones, on a total of 459 km, over the 16-weeks macrocycle prior to off-season.

<b>Training zones</b>	<b>Distance (km)</b>	<b>%</b>
Aerobic capacity	414	90.3
Aerobic power	16	3.4
Anaerobic lactic capacity	9	1.9
Anaerobic lactic power	6	1.2
Anaerobic alactic	15	3.2

### **Procedures**

Anthropometric profile (body mass, height and arm span) was obtained by an International Society for the Advancement of Kinanthropometry accredited level I anthropometrist. Maturational status was verified by a valid and reliable self-assessment of secondary sexual characteristics (Tanner & Whitehouse, 1976). Total physical activity, obtained by the sum of moderate and vigorous intensity physical activity, was assessed through a weekly self-reported questionnaire (International Physical Activity Questionnaire; Craig et al., 2003). Respiratory and pulmonary gas-exchange data were measured breath-by-breath using a

telemetric portable gas analyzer (K4b<sup>2</sup>, Cosmed, Rome, Italy) connected to a low hydrodynamic resistance respiratory snorkel and valve system (AquaTrainer®, Cosmed, Rome, Italy; Ribeiro et al., 2016). The telemetric portable gas analyzer was calibrated before each testing session and transported along the swimming pool suspended at a 2-m height over the water on a steel cable (de Jesus et al., 2014). Swimmers were familiarised during three months before the PRE testing, three times per week, with a snorkel (Arena swim snorkel SKU: 95257; Tolentino, Italy) and nose clip (Arena nose clip pro SKU: 95204; Tolentino, Italy). In-water starts and open turns were employed given the physical restrictions associated with the equipment (Ribeiro et al., 2016). Heart rate (HR) was monitored continuously by a Polar Vantage NV (Polar Electro Oy, Kempele, Finland) that transmitted the data telemetrically to the K4b<sup>2</sup> portable unit. Capillary blood samples for [La<sup>-</sup>] were collected from an earlobe before exercise and immediately after the T400 at the first, third, fifth and seventh min of the recovery period ([La<sup>-</sup>]<sub>peak</sub>; Lactate Pro analyzer, Arkray, Inc, Kyoto, Japan).

The first 20 s of  $\dot{V}O_2$  data after the onset of exercise (the cardiodynamic phase of the  $\dot{V}O_2$  response) were not considered for  $\dot{V}O_2$  kinetics analysis and errant breaths were omitted by only including those within  $\dot{V}O_2$  local mean $\pm$ 4SD (Sousa, Vilas-Boas, & Fernandes, 2014). Subsequently, individual breath-by-breath  $\dot{V}O_2$  responses were time averaged every 10 s and smoothed using a 3-breath moving average (de Jesus et al., 2014). The on-transient during the T400 was modelled for each swimmer using the mono exponential model described in Equation 1:

$$\dot{V}O_2(t) = A_0 + H(t - TD_p) \cdot A_p (1 - e^{-(t - TD_p)/\tau_p}) \quad (1)$$

where  $\dot{V}O_2(t)$  represents the relative  $\dot{V}O_2$  at the time  $t$ ,  $A_0$  is the  $\dot{V}O_2$  at rest (average from the last 2 min previous to exercise),  $H$  represents the Heaviside step function (Equation 2; Ma, Rossiter, Barstow, Casaburi, & Porszasz, 2010) and  $A_p$ ,  $TD_p$  and  $\tau_p$  are the amplitude, time delay and time constant of the fast  $\dot{V}O_2$  component.

$$H(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases} \quad (2)$$

Since T400 performances were different between swimmers, mean  $\dot{V}O_2$  over the last 30 s of each 100-m interval was calculated to characterise and compare T400  $\dot{V}O_2$  responses (Hanon, Leveque, Thomas, & Vivier, 2008; Ingham, Fudge, Pringle, & Jones, 2013; Zacca et al., 2017). The mean response time (MRT) was obtained as  $TD_p + \tau_p$  and  $\dot{V}O_{2max}$  computed as the average of the last 30 s  $\dot{V}O_2$  values during the T400 since it is well-established that swimmers can reach and sustain the minimal  $v$  that elicits  $\dot{V}O_{2max}$  ( $v\dot{V}O_{2max}$ ) during a 400 m effort (Billat et al., 1996; Fernandes et al., 2006; Zacca et al., 2017).

The estimated  $E_{tot}$  was calculated as the sum of Aer, AnL and AnAL energy contributions, with the Aer and AnL energy calculated from the time integral of the net  $\dot{V}O_2$  versus time relationship and using the Equation 3, respectively (Sousa et al., 2014):

$$AnL = [La^-]_{net} \cdot \beta \cdot M \quad (3)$$

where  $[La^-]_{net}$  is the difference between the  $[La^-]$  before and after exercise ( $[La^-]_{peak}$ ),  $\beta$  is the constant for  $O_2$  equivalent of  $[La^-]_{net}$  ( $2.7 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{mM}^{-1}$ ; Thevelein, Daly, & Persyn, 1984) and  $M$  is the body mass of the swimmer. These energy contributions were then expressed in kJ assuming an energy equivalent of  $20.9 \text{ kJ} \cdot \text{L}^{-1}$  (Zamparo, Capelli, & Pendergast, 2011). The AnAL energy was estimated from the maximal phosphocreatine (PCr) splitting in the contracting muscle (Equation 4; Sousa et al., 2014; Binzoni, Ferretti, Schenker, & Cerretelli, 1992):

$$AnAL = PCr \cdot (1 - e^{-t/\tau}) \cdot M \quad (4)$$

where PCr is the phosphocreatine concentration at rest,  $t$  is the exercise time,  $\tau$  is time constant of the PCr splitting at exercise onset (23.4 s) and  $M$  is the body mass. Subsequently, AnAL was expressed in kJ by assuming an energy

equivalent of  $0.468 \text{ kJ}\cdot\text{mM}^{-1}$  and a phosphate/oxygen ratio of 6.25 (Zamparo et al., 2011). C was obtained as the ratio between  $E_{tot}$  and distance (Fernandes et al., 2006; Zamparo et al., 2011).

Surface and underwater video cameras (50 Hz, Sony® Handycam HDR-CX130, Japan) recorded 10-m of the last 25-m of each 100-m interval (within two points at 7.5 m from each end of the swimming-pool to exclude the influence of the turning phase). Cameras were synchronised with Adobe Premiere Pro CC (v2015, Adobe Systems, San Jose, California, USA) through a light flash activated prior to each trial. The  $v$  from each 100-m interval was measured from the time taken to cover the middle 10-m of each length ( $v = d/t_{10}$ , where  $d = 10\text{-m}$  and  $t_{10} = \text{time for the } 10 \text{ m}$ ) and the  $v$  of T400 was calculated as the mean of the four 100-m intervals. Stroke rate (SR) was computed from the time taken to complete three consecutive upper limbs cycles, stroke length (SL) calculated from the ratio between  $v$  and corresponding SR and stroke index (SI), a measure of swimming efficiency, calculated by multiplying  $v$  by SL (Zacca et al., 2017). Inter-limb coordination was assessed by the Index of Coordination (IdC; Figueiredo, Toussaint, Vilas-Boas, & Fernandes, 2013; Seifert et al., 2014), where the lag time between the propulsive phases of each upper limb (two cycles) was calculated and expressed as a percentage of the overall duration of the upper limbs cycle.

### **Statistical Analysis**

A longitudinal cohort study analysis with PRE and POST repeated measures (performance, physiological and biomechanical related variables, controlling anthropometric and non-swimming physical activity) was performed. Normality and homogeneity were verified with the Shapiro–Wilk’s and Levene’s Tests (respectively). Mean and SD for descriptive analysis were obtained and reported for all studied variables. A Fisher’s test was used to test for eventual differences in pubertal stage between male and female swimmers. Possible gender effects (covariate) between PRE and POST paired means for all variables were verified a priori. Bootstrapping with 1000 samples was used to estimate  $\dot{V}O_2$  kinetics parameters and respective coefficient of variation. A paired t-test was used to compare differences between PRE and POST off-season for each variable. Effect sizes (Cohen’s  $d$ ) were calculated with the following criteria: 0 to 0.19 trivial,

0.2 to 0.59 small, 0.6 to 1.19 moderate, 1.2 to 1.99 large, 2.0 to 3.99 very large and > 4.0 nearly perfect (Hopkins, 2002).

Partial correlations, conditioning on gender, were used to quantify the degree of association between deltas ( $\Delta$ , i.e., POST values subtracted by PRE values) for each variable and the change in T400 performance, interpreted as follows: < 0.40 poor, 0.40-0.75 fair to good and > 0.75 excellent (Fleiss, 1986). Repeated measures analysis of variance (ANOVA) was performed with PRE and POST performances using the change score values of height, body mass and arm span, and the total physical activity during off-season as a covariate to control the effects of anthropometric changes and non-swimming specific physical activities performed during off-season. Eta squared ( $\eta^2$ ) test was used to quantify the percentage of the variance explained by each covariate (effect size) and interpreted as follows:  $0 < \eta^2 < 0.04$  without effect,  $0.04 \leq \eta^2 \leq 0.24$  minimum,  $0.25 \leq \eta^2 < 0.64$  moderate and  $\eta^2 \geq 0.64$  large effect (Ferguson, 2009). Alpha significance level was established at 0.05.

## Results

As trivial gender differences ( $p = 0.06$  to  $0.97$ ;  $\eta^2 = 0.00$  to  $0.23$ ) were observed for all variables during preliminary data analysis, male and female swimmers data were pooled and analysed as a single group. T400 performance reduced 3.8% (1.4 to 6.1%; mean (95%CI);  $p < 0.01$ ;  $d = 0.90$ ) during the off-season, with the  $v$  being markedly slower at 100-, 200-, 300- and 400-m laps ( $p \leq 0.01$ ;  $d = -5.20$  to  $-1.06$ ; moderate to very large effect) at the POST condition (Table 2). Likewise, SR decreased at all 100-m intervals ( $p \leq 0.01$ ;  $d = -1.27$  to  $-0.77$ ), which influenced SI values (also substantially lower at all 100-m intervals;  $p < 0.05$ ;  $d = -0.94$  to  $-0.66$ ) in the beginning of the new training season. SL ( $p = 0.36$  to  $0.74$ ;  $d = -0.25$  to  $0.09$ ) and IdC ( $p = 0.19$  to  $0.89$ ;  $d = -0.36$  to  $-0.04$ ) were similar between PRE and POST at all 100-m intervals. There was good to excellent inverse associations between changes in SR and T400, with a lower SR at all 100-m intervals at POST being associated with a slower performance time ( $p \leq 0.02$ ). Changes in SL at 100-m,  $v$ , and  $v$  at 200-, 300- and 400-m were also highly correlated with the reduction in swimming performance (good to excellent;  $p \leq 0.03$ ; Table 2).

The  $A_p$  and MRT were similar between PRE and POST conditions and both parameter estimates had a coefficient of variation of 1%).  $\dot{V}O_2$  POST was lower at both the 100 ( $p \leq 0.010$ ;  $d = -1.26$ ) and 200-m intervals ( $p = 0.02$ ;  $d = -0.66$ ), but similar at the 300-m lap ( $p = 0.07$ ;  $d = -0.50$ ) and at the T400 end ( $\dot{V}O_{2max}$ ;  $p = 0.10$ ;  $d = -0.45$ ; Figure 1 and Table 3). The  $[La^-]_{peak}$  at POST was higher than PRE condition ( $p < 0.01$ ;  $d = 0.90$ ) and the heart rate was similar between testing sessions ( $p = 0.49$ ;  $d = -0.18$ ). The Aer energy pathway was similar between conditions, but AnL POST ( $p < 0.01$ ;  $d = 0.92$ ) and AnAL POST ( $p < 0.01$ ;  $d = 0.99$ ) were higher (Table 3). However, Aer contribution at POST was  $\sim 1.8\%$  lower (95%CI: -2.69 to -0.98%;  $p < 0.01$ ;  $d = -1.19$ ) and AnL contribution  $\sim 1.6\%$  higher (0.8 to 2.5%;  $p < 0.01$ ;  $d = 1.08$ ; Table 3). Good correlation value was verified between changes in  $[La^-]_{peak}$  and swimming performance impairment ( $r = -0.52$ ;  $p = 0.05$ ; Table 3).

Height, arm span and weight values were higher in the beginning of the new training season than in the final of the previous one ( $p < 0.05$ ;  $d \geq 0.90$ ), but had little influence on T400 performance changes (Table 4). However, swimming performance loss was attenuated by completion of non-swimming specific physical activities during the off-season ( $1814 \pm 1989$  MET-min  $\cdot$  wk<sup>-1</sup>), as they accounted for 40% of the total variance in performance ( $p = 0.01$ ; partial  $\eta^2 = 0.40$  moderate) and showed good partial correlation with the reduction in T400 performance ( $r = -0.58$ ;  $p = 0.03$ ). Figure 1 shows an integrated view of the detraining effects on performance, energetics and technique after four-weeks off-season (PRE vs POST), particularly the  $\dot{V}O_2$  response,  $v$ ,  $IdC$ , SL and SR during the T400.

**Table 2.** Effects of four-weeks off-season on age-group swimmers technique. There are displayed the PRE and POST mean  $\pm$  SD values with respective level of probabilities (p), mean differences, 95% confidence intervals, relative changes (% $\Delta$ ), effect sizes and partial correlations between deltas and delta performance ( $\Delta$ ).

Variable	PRE	POST	p	Difference [95%CI]; % $\Delta$	Effect size (d)	$\Delta$ vs $\Delta$ Performance partial correlation (p)
Performance (s)	345 $\pm$ 20	358 $\pm$ 21	< 0.01	13 [5, 21]; 3.8%	0.90, moderate	- (-)
v100 (m·s <sup>-1</sup> )	1.14 $\pm$ 0.06	1.08 $\pm$ 0.07	< 0.01	-0.06 [-0.09, -0.03]; -5.3%	-1.20, Large	-0.45 (0.11)
v200 (m·s <sup>-1</sup> )	1.13 $\pm$ 0.07	1.06 $\pm$ 0.07	< 0.01	-0.07 [-0.11, -0.04]; -6.2%	-1.06, Moderate	-0.59 (0.03)
v300 (m·s <sup>-1</sup> )	1.14 $\pm$ 0.07	1.06 $\pm$ 0.06	0.01	-0.08 [-0.13, -0.04]; -7.4%	-1.12, Moderate	-0.77 (< 0.01)
v400 (m·s <sup>-1</sup> )	1.21 $\pm$ 0.09	1.11 $\pm$ 0.07	< 0.01	-0.10 [-0.15, -0.06]; -8.6%	-5.20, Nearly Perfect	-0.68 (0.01)
v (m·s <sup>-1</sup> )	1.16 $\pm$ 0.06	1.08 $\pm$ 0.06	< 0.01	-0.08 [-0.11, -0.05]; -6.9%	-1.40, Large	-0.73 (< 0.01)
SR <sub>100</sub> (cycles·min <sup>-1</sup> )	33.48 $\pm$ 2.33	31.54 $\pm$ 2.50	< 0.01	-1.94 [-3.32, -0.57]; -5.8%	-0.78, Moderate	-0.71 (< 0.01)
SR <sub>200</sub> (cycles·min <sup>-1</sup> )	33.51 $\pm$ 2.67	31.54 $\pm$ 2.72	< 0.01	-1.96 [-3.32, -0.61]; -5.9%	-0.81, Moderate	-0.77 (< 0.01)
SR <sub>300</sub> (cycles·min <sup>-1</sup> )	33.91 $\pm$ 3.19	31.82 $\pm$ 2.65	0.01	-2.09 [-3.59, -0.59]; -6.2%	-0.77, Moderate	-0.85 (< 0.01)
SR <sub>400</sub> (cycles·min <sup>-1</sup> )	35.61 $\pm$ 2.96	32.76 $\pm$ 2.62	< 0.01	-2.85 [-4.09, -1.61]; -8.0%	-1.27, Large	-0.61 (0.02)
SL <sub>100</sub> (m)	2.06 $\pm$ 0.18	2.07 $\pm$ 0.19	0.74	0.01 [-0.05, 0.07]; 0.5%	0.09, Trivial	0.60 (0.02)
SL <sub>200</sub> (m)	2.04 $\pm$ 0.19	2.03 $\pm$ 0.22	0.71	-0.01 [-0.08, -0.06]; -0.6%	-0.09, Trivial	0.44 (0.12)
SL <sub>300</sub> (m)	2.04 $\pm$ 0.19	2.01 $\pm$ 0.18	0.36	-0.03 [-0.09, 0.04]; -1.4%	-0.25, Small	0.37 (0.19)
SL <sub>400</sub> (m)	2.06 $\pm$ 0.19	2.04 $\pm$ 0.19	0.71	-0.02 [-0.09, 0.06]; -0.7%	-0.10, Trivial	0.03 (0.92)
SI <sub>100</sub> (m <sup>2</sup> ·s <sup>-1</sup> )	2.4 $\pm$ 0.3	2.2 $\pm$ 0.3	0.02	-0.11 [-0.21, -0.02]; -4.8%	-0.66, Moderate	0.11 (0.70)
SI <sub>200</sub> (m <sup>2</sup> ·s <sup>-1</sup> )	2.3 $\pm$ 0.3	2.1 $\pm$ 0.3	0.01	-0.16 [-0.28, -0.04]; -7.0%	-0.76, Moderate	-0.10 (0.73)
SI <sub>300</sub> (m <sup>2</sup> ·s <sup>-1</sup> )	2.3 $\pm$ 0.3	2.1 $\pm$ 0.3	< 0.01	-0.20 [-0.32, -0.08]; -8.6%	-0.94, Moderate	-0.31 (0.28)
SI <sub>400</sub> (m <sup>2</sup> ·s <sup>-1</sup> )	2.5 $\pm$ 0.4	2.3 $\pm$ 0.3	< 0.01	-0.24 [-0.39 to -0.08]; -9.4%	-0.83, Moderate	-0.45 (0.11)
IdC <sub>100</sub> (%)	-9.3 $\pm$ 3.5	-10.1 $\pm$ 3.3	0.19	-0.8 [-2.0, 0.4]; 8.6%	-0.36, Small	-0.11 (0.70)
IdC <sub>200</sub> (%)	-9.3 $\pm$ 4.2	-9.7 $\pm$ 3.7	0.74	-0.4 [-3.0, 2.2]; 4.3%	-0.09, Trivial	0.47 (0.09)
IdC <sub>300</sub> (%)	-9.5 $\pm$ 5.0	-9.7 $\pm$ 3.2	0.89	-0.2 [-3.1, 2.7]; 2.1%	-0.04, Trivial	0.30 (0.30)
IdC <sub>400</sub> (%)	-8.5 $\pm$ 4.1	-9.7 $\pm$ 3.8	0.43	-1.1 [-4.1, 1.9]; 13.3%	-0.21, Small	0.44 (0.12)

v: swimming speed; SR: stroke rate; SL: stroke length; SI: stroke index; IdC: index of coordination.



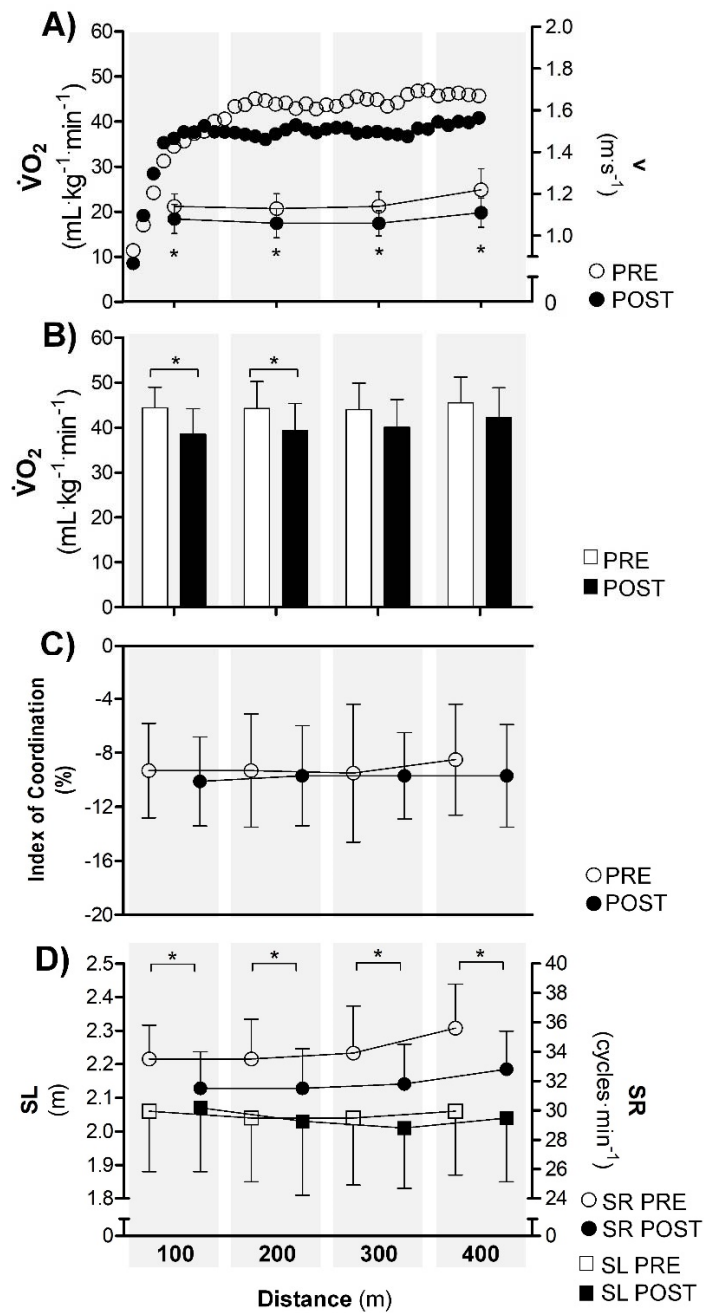
**Table 3.** Effects of four-weeks off-season on age-group swimmers energetics. There are displayed the PRE and POST mean  $\pm$  SD values with respective level of probabilities (p), mean differences, 95% confidence intervals, relative changes (% $\Delta$ ), effect sizes and partial correlations between deltas and delta performance ( $\Delta$ ).

Variable	PRE	POST	p	Difference [95%CI]; % $\Delta$	Effect size (d)	$\Delta$ vs $\Delta$ Performance partial correlation (p)
MRT (s)	43.2 $\pm$ 10.3	46.8 $\pm$ 17.1	0.36	3.6 [-4.5, 11.6]; 8.3%	0.25, Small	0.34 (0.24)
A <sub>p</sub> (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	36.4 $\pm$ 6.0	32.9 $\pm$ 6.4	0.11	-3.4 [-7.8, -0.9]; -9.3%	-0.44, Small	-0.17 (0.55)
$\dot{V}O_2$ 100 (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	44.4 $\pm$ 4.6	38.5 $\pm$ 5.7	< 0.01	-5.9 [-8.5, -3.3]; -13.3%	-1.26, Large	-0.20 (0.48)
$\dot{V}O_2$ 200 (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	44.2 $\pm$ 6.0	39.3 $\pm$ 6.1	0.02	-4.9 [-9.1, -0.8]; -11.2%	-0.66, Moderate	-0.29 (0.31)
$\dot{V}O_2$ 300 (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	44.0 $\pm$ 5.9	40.1 $\pm$ 6.2	0.07	-3.9 [-8.2, 0.4]; -8.9%	-0.50, Small	-0.38 (0.18)
$\dot{V}O_2$ 400 ( $\dot{V}O_{2max}$ ) (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	45.4 $\pm$ 5.7	42.3 $\pm$ 6.6	0.10	-3.1 [-7.0, 0.7]; -7.0%	-0.45, Small	-0.31 (0.27)
$\dot{V}O_2$ 400 ( $\dot{V}O_{2max}$ ) (L·min <sup>-1</sup> )	2.68 $\pm$ 0.47	2.58 $\pm$ 0.6	0.38	-0.10 [-0.33, 0.14]; -3.7%	-0.23, Small	-0.48 (0.08)
[La] <sub>peak</sub> (mmol·L <sup>-1</sup> )	4.5 $\pm$ 1.4	6.2 $\pm$ 2.4	< 0.01	1.7 [0.7, 2.8]; 38.0%	0.90, Moderate	-0.52 (0.05)
HR (bpm)	185 $\pm$ 8	184 $\pm$ 7	0.49	-1 [-5, 2]; -0.7%	-0.18, Trivial	-0.47 (0.09)
Aer energy (kJ)	287 $\pm$ 57	281 $\pm$ 57	0.64	-6 [-31, 20]; -1.9%	-0.12, Trivial	-0.21 (0.48)
AnL energy (kJ)	10.75 $\pm$ 5.55	16.70 $\pm$ 9.26	< 0.01	5.95 [2.39, 9.51]; 55.4%	0.92, Moderate	-0.48 (0.08)
AnAL energy (kJ)	24.82 $\pm$ 4.41	25.45 $\pm$ 4.38	< 0.01	0.63 [0.27, 0.98]; 2.5%	0.99, Moderate	-0.34 (0.23)
Aer contribution (%)	88.90 $\pm$ 2.46	87.06 $\pm$ 1.92	< 0.01	-1.83 [-2.69, -0.98]; -2.1%	-1.19, Moderate	0.41 (0.14)
AnL contribution (%)	3.32 $\pm$ 1.73	4.96 $\pm$ 2.13	< 0.01	1.63 [0.79, 2.47]; 49.4%	1.08, Moderate	-0.50 (0.07)
AnAL contribution (%)	7.78 $\pm$ 1.06	7.98 $\pm$ 1.06	0.55	0.20 [-0.49, -0.90]; 2.5%	0.16, Trivial	0.18 (0.54)
E <sub>tot</sub> (kJ)	322.3 $\pm$ 57.0	324.0 $\pm$ 66.7	0.89	1.7 [-25.8, 29.3]; 0.5%	0.03, Trivial	-0.27 (0.34)
C (kJ·m <sup>-1</sup> )	0.80 $\pm$ 0.14	0.81 $\pm$ 0.17	0.92	0.01 [-0.06, 0.07]; 1.2%	0.02, Trivial	-0.28 (0.34)

MRT: mean response time; A<sub>p</sub>: amplitude of the fast  $\dot{V}O_2$  component;  $\dot{V}O_2$ : oxygen uptake; [La]<sub>peak</sub>: peak blood lactate; HR: heart rate; Aer: aerobic; AnL: anaerobic lactic; AnAL: anaerobic alactic; E<sub>tot</sub>: total energy expenditure; C: energy cost

**Table 4.** Effects of four-weeks off-season on age-group swimmers anthropometrics. There are displayed the PRE and POST mean  $\pm$  SD values with respective level of probabilities ( $p$ ), mean differences, 95% confidence intervals, relative changes ( $\% \Delta$ ), effect sizes and partial correlations between deltas and delta performance ( $\Delta$ ).

Variable	PRE	POST	$p$	Difference [95%CI]; $\% \Delta$	Effect size ( $d$ )	$\Delta$ vs $\Delta_{\text{Performance}}$ Partial Correlation ( $p$ )
Height (cm)	164.3 $\pm$ 6.2	165.7 $\pm$ 5.8	< 0.01	1.4 [0.7, 2.4]; 0.9%	1.05, moderate	0.30 (0.31)
Arm span (cm)	167.5 $\pm$ 8.3	168.7 $\pm$ 8.8	< 0.01	1.2 [0.5, 1.9]; 0.7%	0.98, moderate	0.40 (0.16)
Body mass (kg)	59.6 $\pm$ 10.3	61.1 $\pm$ 10.5	< 0.01	1.5 [0.6, 2.4]; 2.5%	0.98, moderate	-0.34 (0.23)



**Fig 1.** Integrated view of the off-season effect (n=15). Typical  $\dot{V}O_2$  response (averaged every 10 s) to a 400-m test in front crawl (T400) performed by all swimmers (left axis A panel), swimming speed (right axis A panel),  $\dot{V}O_2$  (B panel), Index of Coordination (C panel), stroke length (left axis D panel) and stroke rate (right axis D panel) for each 100-m interval. Error bars are standard deviations for each plot. \*  $p < 0.05$  between PRE and POS tests were identified for  $v$  (100 - 400 intervals),  $\dot{V}O_2$  (100 - 200-m intervals) and SR (100 - 400-m intervals).

## Discussion

Swimmers showed a substantial decrease in performance after four-weeks of training cessation, despite the sustained MRT,  $A_p$  and  $\dot{V}O_{2max}$  values. Although the Aer contribution decreased  $\sim 1.8\%$  and the AnL contribution increased  $\sim 1.6\%$ ,  $E_{tot}$  and C remained similar after the off-season. The impaired performance was mainly associated with lower SR (at all 100-m intervals), SL (only in the 100-m lap),  $[La]_{peak}$  and non-swimming specific physical activities conducted during the off-season. Although the height, arm span and weight values increased after four-weeks of training cessation, they did not significantly account for variance in performance decrements. However, impairment in swimming performance was attenuated in those swimmers who were more physically active during the detraining period.

Selected physiological and biomechanical determinants of swimming performance start to decay when the training process is broken, leading to detraining and reduced performance (Billat et al., 1996; Mujika & Padilla, 2000). Although PRE and POST  $E_{tot}$  and C values were similar, other physiological and biomechanical markers contributed to maintenance of performance after the off-season. Although MRT,  $A_p$ ,  $\dot{V}O_{2max}$  and Aer energy pathway were essentially unchanged over four-weeks of training cessation, the Aer contribution decreased by  $\sim 1.8\%$ , particularly during the first 200-m where  $\dot{V}O_2$  was lower. The AnL energetic contribution increased from PRE to POST, correlating negatively with T400 swimming performance (Table 3) increasing the contribution to  $E_{tot}$  by  $\sim 1.6\%$ . Although similar SL were exhibited in-between evaluations, these changes in energy contributions were associated with lower SR values. However,  $E_{tot}$  and C remained unchanged, and their trivial delta values were not correlated with change in swimming time-trial performance. Thus, energy pathways and respective contributions were more sensitive variables than  $E_{tot}$  and C to identify the modest changes in energetics after the off-season. It seems that a lower aerobic metabolism efficiency and a higher anaerobic contribution make it harder for a swimmer to sustain the  $v$  reached prior to the off-season period.

The observed  $E_{tot}$  and C values are in line with the literature (Fernandes et al., 2006; Sousa et al., 2013; Ribeiro et al., 2017) and, although both are associated with swimming performance, they rely on a swimmer's level and  $v$  to accomplish

a certain distance. The  $v$  provides overall information about a swimmer's status, with its kinetics a product of technical pattern, reflecting the balance between propulsive and drag forces (related to motor control). The  $v$  was lower after four-weeks of training cessation regardless the absence of a marked difference in  $\dot{V}O_{2max}$ . This  $v$ , assumed as corresponding to the  $v\dot{V}O_{2max}$ , distinguishes individual differences in performance that  $\dot{V}O_{2max}$  or  $C$  alone could not identify, with swimmers with similar  $\dot{V}O_{2max}$  may presenting different performance times (Billat et al., 1996; Daniels, 2013, Zacca et al., 2017). In fact, changes in  $v\dot{V}O_{2max}$  were associated with individual differences in the T400 performance that  $\dot{V}O_{2max}$  or  $C$  did not identify. Therefore, coaches and researchers should focus on  $v\dot{V}O_{2max}$  rather than  $\dot{V}O_2$  and/or  $C$  while evaluating energetics in age-group swimmers.

Regarding swimming technique, it is relevant to highlight the importance of the pull and push as main propulsive phases in front crawl (Figueiredo, Toussaint, Vilas-Boas, & Fernandes, 2013; Seifert et al., 2014). Theoretically, a continuous swimming motor pattern can minimise the  $C$  (lower intra-cyclic speed variation; Figueiredo, Toussaint, Vilas-Boas, & Fernandes, 2013; Seifert et al., 2014). However, intra- and inter-individual adaptations occur when accomplishing a given task-goal, meaning that the coordination pattern variability leads to functional adaptations to constraints. Thus, even in the absence of ideal coordination patterns that swimmers should replicate (Seifert et al., 2014), the current study IdC PRE and POST values reflected the same coordination mode (*catch-up*) across all the T400 100-m intervals. Swimming efficiency (SI) for all 100-m intervals decreased after the detraining period, as a function of lower SR (despite similar values of SL). However, SI changes were not correlated with swimming performance, probably because the SR and SL biomechanical patterns were not identical for all swimmers.

Our expectation that young adolescent swimmers growth during the off-season period and contributions of non-swimming physical activity might offset the detraining related to swimming capacities was partially supported by the current results, in line with previous reports (Ayabakan et al., 2006; Csajagi et al., 2015; Kavouras & Troup, 1996). Likewise, even after ~10-weeks of training cessation, 12-13 y old swimmers improved swimming biomechanics as a function of growth

and maturation (Moreira et al., 2014). However, POST anthropometric variables related to growth did not account for variance in performance after the four-weeks of training cessation. The amount of physical activity performed in the transition period in-between training seasons accounted for 40% of the total performance variance, and the swimming performance decrease was lower in more physically active swimmers. Thus, swimmers should be physically active when enjoying the off-season to minimise the decline in swimming performance.

## **Conclusion**

Detraining after four-weeks of pool-based training cessation can impair swimming performance at the start of the following training season in age-group swimmers, highlighting the importance of maintaining fitness levels during off-season. Swimming performance at the 400 m front crawl was reduced by 3.8% after four-weeks of training cessation in competitive 14-15 years old swimmers. Impaired performance was mainly associated with reductions in SR, increase in  $[La^-]_{peak}$  and non-swimming specific physical activities. Although four-weeks was not long enough to detect a growth effect on performance, impairment of T400 performance was attenuated by those swimmers who were more physically active during the off-season. Thus, coaches should provide instructions for age-group swimmers to be physically active when enjoying the off-season. Running or cycling for aerobic conditioning, and dryland workouts (such as dry land sports, cross-training or gym-based exercises) could be helpful in minimising swimming performance loss during the transition to the following competitive season.

## **Disclosure of interest**

No potential conflict of interest was reported by the authors.

## Chapter 5.

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### **Monitoring age-group swimmers over a training macrocycle: energetics, technique and anthropometrics**

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The Journal of Strength and Conditioning Research

## **ABSTRACT**

The aim of this study was to quantify changes and contributions of energetic, technique and anthropometric profiles across the first training macrocycle (16-week) in a traditional three-peak swimming season. Twenty-four age-group swimmers (10 males and 14 females age  $14.4 \pm 0.9$  y) of equal maturational stage were monitored through a 400-m test in front crawl (T400). Energetic, technique and anthropometric characteristics were compared before (experimental testing 1, E1) and after the preparatory (E2), specific (E3) and competitive (E4) training periods. Gender interaction was not significant for any variable. Multiple linear regressions and principal component analysis were used to identify the most influential variables and the relative contribution of each domain (energetics, technique and anthropometrics) to changes in swimming performance of T400. The relative contributions for performance of T400 at E1, E2, E3 and E4 were respectively 15, 12, 6, and 13% for energetics, 78, 85, 75, and 70% for technique, and 7, 3, 19 and 17% for anthropometrics. Technique played the main role during the first 16-week macrocycle in a competitive season, regardless of small fluctuations in the influence of energetics and anthropometrics. Changes and influence of energetics, technique and anthropometric on age-group swimmers' performance could be described by the T400 swimming test, providing a comprehensive biophysical overview of the main contributors to swimming performance.

**KEY WORDS:** Swimming; Training Periodization; Physiology, Biomechanics, Anthropometry; Longitudinal



## INTRODUCTION

Competitive swimming is a complex sport in which performance is determined by several factors. Changes in energetics, technique and anthropometrics factors, associated with performance, provide important insights into a swimmer's preparation for competition. However, detailed information on parallel changes in these measures, and their relationship to swimming performance, are difficult to obtain in the aquatic environment (1,5,21). Conclusive information about the relationships among swimming determinant variables and performance during training phases cannot easily be provided by cross-sectional swimming-related studies. Therefore, longitudinal data on swimmers training are required.

The dynamic process of training periodization is one of the most important branches of training theory in the sports context (12,14). The upper level of the hierarchical periodized system belongs to the multi-year preparation, followed by the macrocycles, which are often composed of three training periods in a given season or year. The initial preparatory period typically contains more high-volume training performed at low to moderate intensities, and diversified exercises to develop general physical and technical abilities. The second training period focuses on more event-specific work, and the third period, the competition period, includes more race pace-specific exercises and reduced volume. Despite these constructs there are few data available on the pattern of changes in key measures during a training season.

Longitudinal studies in age-group swimmers indicate that cardiac morphology and performance are reliant on anthropometrics and training stimuli (1,5,16). Likewise, immunological, psychological, hormonal, hematological and other physiological alterations have been observed in elite swimmers (21,29,30) but their relationship with change(s) in performance has not always been reported. Performance during a swimming event depends on the conversion of metabolic into mechanical power through a given energetic efficiency (9). The total energy expenditure ( $E_{tot}$ ), the sum of aerobic (Aer), anaerobic lactic (AnL) and anaerobic alactic (AnAL) energy contributions during different events, metabolic power ( $\dot{E}$ ) and the energy cost (C; the energy consumed to cover one unit of distance while swimming at a given speed), have been estimated through indirect calorimetry

(32). These methods are sufficiently robust and practical to implement in routine testing for both junior and senior swimmers.

The oxygen uptake ( $\dot{V}O_2$ ) and blood lactate concentrations ( $[La^-]$ ) for a given swimming effort can change within the macrocycle in responses to the manipulation of training volume, intensities and loads by the coach. Maximal oxygen uptake ( $\dot{V}O_{2max}$ ) is a commonly reported physiological parameter of aerobic function in swimming. Analysis of the interactions between the dynamic  $\dot{V}O_2$  response following the onset of exercise ( $\dot{V}O_2$  kinetics) and its underlying parameters is needed to quantify the energetic-related determinants of performance (26). To date no study has yet quantified the  $\dot{V}O_2$  kinetics across a traditional macrocycle in age-group swimmers. It is plausible that substantial changes in  $\dot{V}O_2$  related parameters,  $E_{tot}$ ,  $\dot{E}$  and  $C$  can be observed in parallel with improvements in performance during the first macrocycle of a competitive season in age-group swimmers.

Age-group swimmers technique is developed through training, coaching instruction and deliberate practice, which underpins improvements in swimming performance over a training season (2,20). Changes in hydrodynamic characteristics in age-group swimmers during a training season are explained by the interplay between growth and training periodization. Despite the marked intra- and inter-subject variability in these parameters, hydrodynamics and kinematics appear to influence performance during one training season in age-group swimmers (20).

Changes in an anthropometric profile affect technique (28), which influences energetics and thus swimming performance. Since energetics, technique and anthropometrics are closely related with swimming performance (17), it is critical for coaches to better understand the relationship between these areas with the training employed over a training macrocycle. The aim of this study was to quantify the changes in the energetics, technique and anthropometric profile while following age-group swimmers over a training season, particularly in the first macrocycle of a traditional three-peak preparation program. Comparing the variations in these profiles, and determining their relative contributions to performance, will inform the evaluation and prescription of age-group swimming training programs.

## **METHODS**

### **Experimental Approach to the Problem**

A single-group prospective study was conducted, and swimmers were tested during a traditional macrocycle training program, before (E1) and after the preparatory (E2), specific (E3) and competitive (E4) training periods of the first macrocycle of a traditional three-peak preparation program (one competitive season). Repeated measures of performance-related physiological, biomechanical and anthropometric variables were obtained. The first experimental testing (E1) took place at the first week of the preparatory training period. The second experimental testing (E2) was conducted six weeks later, during the first week of the specific training period. The third experimental testing (E3) was conducted another six weeks later, during the first week of the competitive training period. The last experimental testing (E4) was conducted three weeks later, 48 h after the main competition of the macrocycle, in the transition period.

Pubertal maturation stage was assessed prior to the first experiment and anthropometric variables were measured in all testing sessions. The experimental testing took place in a 25-m indoor pool with a mean water temperature of 27.6°C, air temperature 25.8°C, and relative humidity 66%. After an ~800-m moderate intensity front crawl warm-up, swimmers performed a 400-m maximal effort front crawl swim test (T400) for performance, physiological and biomechanical assessment. The T400 was chosen given its validity and utility for assessing aerobic power in age-group swimmers (31,40). All participants avoided vigorous exercise in the previous 24 h, were well-hydrated, abstained from caffeine for at least 3 h before testing and encouraged verbally during the T400.

### **Participants**

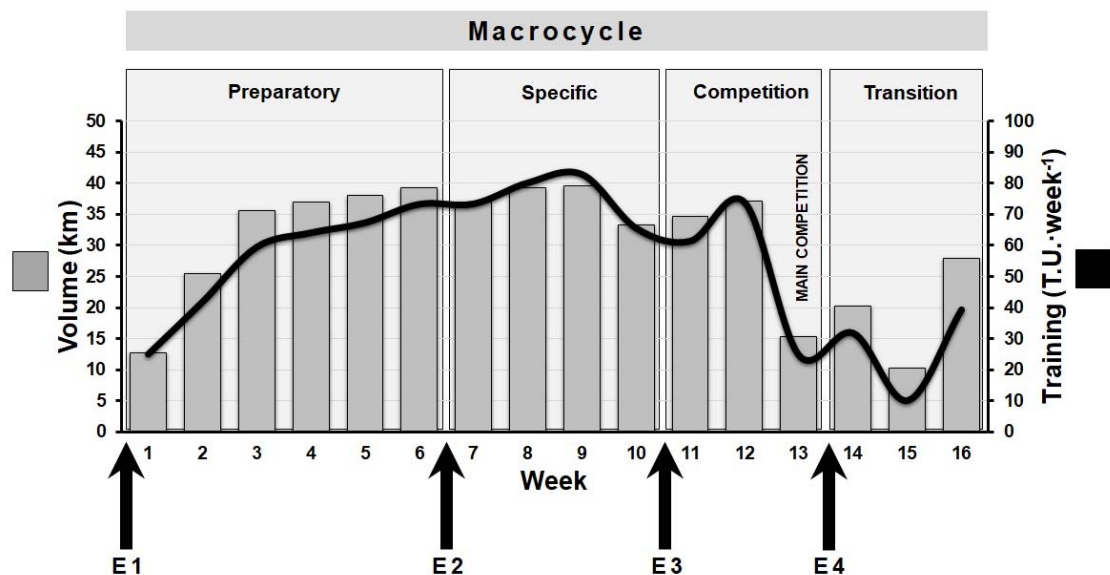
Twenty-four late to post-pubertal age-group swimmers, 10 males and 14 females (14.9 ± 1.0 and 14.2 ± 0.8 y, respectively), volunteered to take part in the current study. Swimmers had over 5 y of competitive experience and trained six to seven swimming sessions and two to three hours of dryland training per week in the same squad and under direction of the same coach.

## Study design

This single-group prospective study followed a longitudinal design. Swimmers parents were informed about the benefits and risks of taking part in the current study prior to signing an informed consent form, which was approved by the ethics board of the local university and performed according to the Helsinki Declaration.

## Procedures

Standard methodologies were used to quantify the swimming training workload (22). Swimming and dry land training (mainly strength and power training sessions) were categorized in different training zones. Swimming distance values were multiplied by the intensity factor and totalled. The magnitude of the load was expressed in arbitrary training units (T.U.), quantified from the calculated sum of the volumes swam in each of the zones, multiplied by the respective intensity factor, and the total volume effectively completed. Dry land training activities were quantified by time and converted to swimming distance (22). The swimmers' T.U. and volume were monitored during a 16-weeks macrocycle. Figure 1 summarizes the training volume and load (T.U.) over the 16-weeks macrocycle.



**Fig 1.** Weekly training load for the entire group of swimmers during the 16-weeks of the first macrocycle of the training season. Values of volume and load are in km and T.U. (training unit), respectively.

An anthropometric profile (body mass, height, arm span and body mass index, BMI) was obtained by an International Society for the Advancement of

Kinanthropometry accredited level I anthropometrist. Maturation status was verified by a valid and reliable self-assessment of secondary sexual characteristics (34).

Respiratory and pulmonary gas-exchange data were measured breath-by-breath using a telemetric portable gas analyzer (K4b<sup>2</sup>, Cosmed, Rome, Italy) connected to a low hydrodynamic resistance respiratory snorkel and valve system (AquaTrainer®, Cosmed, Rome, Italy) (27). The telemetric portable gas analyzer was calibrated before each testing session and transported along the swimming pool suspended at a 2 m height over the water on a steel cable (6). Swimmers were familiarized during three months before the first testing, three times per week, with a snorkel (Arena swim snorkel SKU: 95257; Tolentino, Italy) and nose clip (Arena nose clip pro SKU: 95204; Tolentino, Italy). In-water starts and open turns were employed given the physical restrictions associated with the equipment (26). Heart rate (HR) was monitored continuously by a Polar Vantage NV (Polar Electro Oy, Kempele, Finland) that transmitted the data telemetrically to the K4b<sup>2</sup> portable unit. Capillary blood samples for [La<sup>-</sup>] were collected from an earlobe before exercise and immediately after the T400 at the first, third, fifth and seventh min of the recovery period ([La<sup>-</sup>]<sub>peak</sub>; Lactate Pro analyzer, Arkray, Inc, Kyoto, Japan).

The first 20 s of  $\dot{V}O_2$  data after the onset of exercise (the cardiodynamic phase of the  $\dot{V}O_2$  response) were not considered for  $\dot{V}O_2$  kinetics analysis, and errant breaths were omitted by only including those within  $\dot{V}O_2$  local mean  $\pm$  4SD (33). Subsequently, individual breath-by-breath  $\dot{V}O_2$  responses were time averaged every 10 s and smoothed using a 3-breath moving average (6). Because the inherent breath-by-breath noise observed in young swimmer's response profiles could mask any clear changes in ventilatory variables (7), the on-transient during the T400 was modelled for each swimmer using the mono exponential model described in equation 1:

$$\dot{V}O_2(t) = A_0 + H(t - TD_p) \cdot A_p (1 - e^{-(t - TD_p)/\tau_p}) \quad (1)$$

where  $\dot{V}O_2(t)$  represents the relative  $\dot{V}O_2$  at the time  $t$ ,  $A_0$  is the  $\dot{V}O_2$  at rest (average from the last 2 min previous to exercise),  $H$  represents the Heaviside step function (Equation 2) (19) and  $A_p$ ,  $TD_p$  and  $\tau_p$  are the amplitude, time delay

and time constant of the fast  $\dot{V}O_2$  component. Bootstrapping with 1000 samples was used to estimate  $\dot{V}O_2$  kinetics parameters.

$$H(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases} \quad (2)$$

The mean response time (MRT) was obtained as  $TD_p + \tau_p$  and  $\dot{V}O_{2max}$  was computed as the mean  $\dot{V}O_2$  over the last 60 s of the T400 (10,13,40). The amplitude of the slow  $\dot{V}O_2$  component ( $A_{sc}$ ) was estimated as the difference between the  $\dot{V}O_2$  at the end (average of the last 60 s) and  $A_p + A_0$ .

The  $E_{tot}$  was estimated as the sum of Aer, AnL and AnAL energy contributions, with the Aer and AnL energy calculated from the time integral of the net  $\dot{V}O_2$  versus time relationship and using equation 3, respectively (33):

$$AnL = [La^-]_{net} \cdot \beta \cdot M \quad (3)$$

where  $[La^-]_{net}$  is the difference between the  $[La^-]$  before and after exercise ( $[La^-]_{peak}$ ),  $\beta$  is the constant for  $O_2$  equivalent of  $[La^-]_{net}$  ( $2.7 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{mM}^{-1}$ ) and  $M$  is the body mass of the swimmer (41). These energy contributions were then expressed in kJ assuming an energy equivalent of  $20.9 \text{ kJ} \cdot \text{L}^{-1}$  (41). The AnAL energy was estimated from the maximal phosphocreatine (PCr) splitting in the contracting muscle (Equation 4) (33):

$$AnAL = PCr \cdot (1 - e^{-t/\tau}) \cdot M \quad (4)$$

where PCr is the phosphocreatine concentration at rest,  $t$  is the exercise time,  $\tau$  is time constant of the PCr splitting at exercise onset (23.4 s) and  $M$  is the body mass. Subsequently, AnAL was expressed in kJ by assuming an energy equivalent of  $0.468 \text{ kJ} \cdot \text{mM}^{-1}$  and a phosphate/oxygen ratio of 6.25 (41). The  $C$  was obtained as the ratio between  $E_{tot}$  and distance, and  $\dot{E}$  (kW) was estimated as the ratio between  $E_{tot}$  and performance (s) of T400 (41).

Surface and underwater video cameras (50 Hz, Sony® Handycam HDR-CX130, Japan) recorded 10 m of the last 25 m of each 100-m interval (within two points at 7.5 m from each end of the swimming-pool to exclude the influence of the turning phase). Cameras were synchronized with Adobe Premiere Pro CC (v2015, Adobe Systems, San Jose, California, USA) through a light flash

activated prior to each trial. The  $v$  from each 100-m interval was measured from the time to cover the middle 10 m of each length ( $v = d/t_{10}$ , where  $d = 10$  m and  $t_{10} =$  time for the 10 m) and the  $v$  of T400 was calculated as the mean of the four 100-m intervals. Stroke rate (SR) was computed from the time taken to complete three consecutive upper limbs cycles. Stroke length (SL) was calculated from the ratio between  $v$  and corresponding SR, and stroke index (SI), a measure of swimming efficiency, calculated by multiplying  $v$  by SL (4).

### **Statistical Analyses**

Mean and standard deviation (SD) are presented as descriptive statistics. The Shapiro–Wilk test was used to test normality of the data. One-way ANOVA (using gender as covariate) and Bonferroni post hoc tests were used to analyze differences between each variable along baseline (E1) and after preparatory (E2), specific (E3) and competitive (E4) periods. Eta squared ( $\eta^2$ ) test was used to quantify the percentage of the variance explained by each covariate (effect size) and interpreted as follows:  $0 < \eta^2 < 0.04$  trivial effect,  $0.04 \leq \eta^2 \leq 0.24$  small,  $0.25 \leq \eta^2 < 0.64$  moderate and  $\eta^2 \geq 0.64$  large effect (8).

Principal component analysis was used as the method of extraction (scree plot criterion) to reduce the initial set of variables at each area (energetics: MRT,  $A_p$ ,  $\dot{V}O_2$ ,  $A_{sc}$ ,  $[La^-]_{peak}$ , heart rate,  $A_{er}$ ,  $A_{nL}$ ,  $A_{nAL}$ ,  $E_{tot}$ ,  $\dot{E}$  and  $C$ ; technique: SR, SL and SI; anthropometrics: BMI, height, arm span and body mass) from E1, E2, E3 and E4, while removing the effect of multicollinearity. Then, multiple linear regressions (“Enter” method) were applied to identify the most influential variables and the relative contribution of energetics, technique and anthropometrics to swimming performance (s) of T400 at baseline (E1) and after (using delta values) each training period. These regression analyses were not intended to predict T400 performance, but to determine the influence of energetics, technique and anthropometric performance-related variables during each period of a traditional macrocycle design (9). Statistical significance was set at  $p < 0.05$ . Data were recorded and analysed using SPSS, version 24 (SPSS Inc, Chicago, Ill, USA).

## RESULTS

No variables presented a significant gender interaction, therefore male and female swimmers data were pooled and analysed as a single group. The mean training load (T.U.·week<sup>-1</sup>) for each of the periods was: 55 ± 18 (preparatory), 75 ± 8 (specific), 53 ± 25 (competition) and 27 ± 15 (transition). The mean volume per week (km·week<sup>-1</sup>) for each of the periods was: 31 ± 10 (preparatory), 37 ± 3 (specific), 29 ± 12 (competition) and 19 ± 9 (transition). Progression of volume and training load until two weeks prior to the main competition was ~4.3 and ~10.5%·week<sup>-1</sup>.

### **Changes in technique, energetics and anthropometrics across the macrocycle**

The comparison of technique, energetics and anthropometrics variables along the training periods of the microcycle (baseline, preparatory, specific and competitive) are presented in Table 1. Improvements in 400-m time trial performance during the first macrocycle of the season occurred mainly from baseline to the end of preparatory period (6.6%; 95%CI -3.5 to -10.7%; p<0.001), followed by the specific (2.7%; 95%CI -5.1 to 16.7%; p<0.001) and competitive training period (1.3%; 95%CI -1.9 to -4.2%; p<0.01). The mean SR increased 12.8% (95%CI 2.2 to 23.5%; p=0.016) from baseline (E1) to the end of the preparatory period (E2), 4.5% (95%CI 0.9 to 27.7%; p=0.032) from baseline to the end of the specific period and 14.0% (95%CI 2.5 to 25.1%; p=0.015) from baseline to the end of competitive period. The SL and SI remained similar from baseline (E1) to competitive period (E4). In the Energetics domain, mean  $A_p$  (28.2%; 95%CI 2.5 to 53.9%; p=0.03),  $\dot{V}O_2$  (29%; 95%CI 13 to 46%; p=0.001), Aer energy (23%; 95%CI 1 to 43% ; p=0.036),  $E_{tot}$  (18%; 95%CI 0.3 to 36%; p=0.05),  $\dot{E}$  (31%; 95%CI 13 to 48%) and C (18%; 95%CI 0 to 37%; p=0.05) were substantially higher from baseline to specific period. Also, the mean  $\dot{E}$  increased 22% (95%CI 9 to 37%; p=0.002) from baseline to competitive period. Other mean values remained relatively similar across the macrocycle. Regarding anthropometrics, arm span increased from baseline to competitive, preparatory to specific, and from specific to competitive period. Mean values for body mass, height and BMI remained unchanged.



### **Relative contributions to swimming performance**

The beta coefficients for the selected variables are presented in Table 2. Each coefficient represents the underlying contribution to the performance of T400 at baseline (E1) and changes (delta) in performance after preparatory, specific and competition periods. The variation in performance explained during the training periods ranged from 75-93%. The adjusted  $R^2$  for the selected variables were 0.93 ( $P<0.001$ ) for baseline, 0.87 ( $P<0.001$ ) for preparatory period, 0.93 ( $P<0.001$ ) for specific period and 0.75 ( $P<0.001$ ) competitive period.

**Table 1.** Data variation (time effect; one-way ANOVA) and changes in technique, energetics and anthropometrics variables in response to a 400-m test in front crawl (T400) performed by all swimmers over the first macrocycle of the training season.

	Time effect				Baseline (E1)		Preparatory (E2)			Specific (E3)			Competitive (E4)		
	F	p-value	Eta <sup>2</sup>	Power	Mean	±SD	Mean	±SD	Δ (%) E1vsE2	Mean	±SD	Δ (%) E2vsE3	Mean	±SD	Δ (%) E3vsE4
<b>TECHNIQUE</b>															
Performance (s)	12.93	0.00 <sup>†</sup>	0.56	0.99	351	27	328*	25	-6.6	320*	16	-2.7	315*	22	-1.3
v (m·s <sup>-1</sup> )	8.53	0.00 <sup>†</sup>	0.46	0.99	1.11	0.08	1.18*	0.09	6.7	1.20*	0.06	1.7	1.21*	0.08	0.4
SR (cycles·min <sup>-1</sup> )	2.45	0.08	0.20	0.55	31.4	3.5	35.4*	2.2	12.8	35.9*	2.6	1.4	35.8*	2.2	-0.4
SL (m)	0.17	0.91	0.02	0.08	2.13	0.18	2.01	0.18	-5.8	2.02	0.19	0.5	2.03	0.14	0.4
SI (m <sup>2</sup> ·s <sup>-1</sup> )	1.54	0.22	0.13	0.36	2.37	0.29	2.39	0.36	0.8	2.44	0.33	2.1	2.46	0.31	0.9
<b>ENERGETICS</b>															
MRT (s)	0.92	0.44	0.09	0.22	41.4	22.3	36.0	11.8	-13.1	35.6	29.4	-1.2	27.4	7.4	-22.9
A <sub>p</sub> (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	4.96	0.00 <sup>†</sup>	0.35	0.87	31.5	3.8	39.5	9.2	25.2	40.4*	7.2	2.3	37.8	6.0	-6.3
VO <sub>2</sub> (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	6.97	0.00 <sup>†</sup>	0.41	0.96	41.6	5.8	48.0	10.3	15.4	53.8*	7.1	12.2	49.9	5.2	-7.4
A <sub>sc</sub> (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	0.34	0.79	0.04	0.11	2.05	2.85	2.34	1.86	13.9	2.56	2.29	9.7	2.25	1.75	-12.1
[La <sup>-</sup> ] <sub>peak</sub> (mmol·L <sup>-1</sup> )	2.41	0.08	0.19	0.54	5.9	2.1	4.7	1.4	-22.0	4.7	1.3	2.0	5.5	1.5	16.3
HR (bpm)	1.11	0.36	0.10	0.27	184	8	181	8	-1.5	183	7	1.1	187	8	2.1
Aer energy (kJ)	4.69	0.00 <sup>†</sup>	0.32	0.85	270	54	297	73	9.9	331*	63	11.4	301	42	-8.9
AnL energy (kJ)	2.38	0.08	0.19	0.54	16.2	8.5	11.9	5.0	-26.3	12.8	6.2	7.5	15.5	7.1	21.1
AnAL energy (kJ)	0.91	0.44	0.08	0.22	25.5	5.2	25.5	4.6	0.0	25.5	4.2	-0.04	25.8	4.6	1.4
Aer contribution (%)	5.03	0.02 <sup>†</sup>	0.33	0.71	86.6	3.2	88.5*	2.5	1.9	89.6*	1.6	1.1	88.0	2.1	-1.6
AnL contribution (%)	4.01	0.04 <sup>†</sup>	0.28	0.60	5.1	2.5	3.6	1.4	-1.5	3.3	1.2	-0.3	4.4	1.7	1.1
AnAL contribution (%)	2.99	0.04 <sup>†</sup>	0.23	0.64	8.2	1.3	7.8	1.4	-0.4	6.9	0.8	-0.9	7.5	0.5	0.6
E <sub>tot</sub> (kJ)	4.02	0.01 <sup>†</sup>	0.29	0.79	312	61	334	79	7.2	369*	71	10.4	342	49	-7.1
Ė (kW)	9.17	0.00 <sup>†</sup>	0.48	0.99	0.90	0.18	1.03	0.29	14.4	1.17*	0.27	13.6	1.10*	0.21	-5.9
C (kJ·m <sup>-1</sup> )	4.02	0.01 <sup>†</sup>	0.29	0.79	0.78	0.15	0.84	0.20	7.2	0.92*	0.18	10.4	0.86	0.12	-7.2
<b>ANTHROPOMETRICS</b>															
Height (cm)	0.58	0.63	0.05	0.17	165.9	7.8	166.4	7.8	0.3	167.1	7.2	0.4	167.3	7.3	0.1
Body mass (kg)	0.91	0.44	0.08	0.22	61.2	12.4	61.2	11.1	0.0	61.2	10.1	-0.04	62.0	11.1	1.4
Arm Span (cm)	6.83	0.00 <sup>†</sup>	0.40	0.96	172.1	10.2	173.0	10.0	0.5	173.1*	10.1	0.05	174.0* <sup>#&amp;</sup>	9.8	0.4
BMI	0.85	0.47	0.07	0.21	22.0	3.1	21.9	2.4	-0.4	21.8	2.1	-0.8	22.0	2.6	1.1

v: swimming speed; SR: stroke rate; SL: stroke length; SI: stroke index; MRT: mean response time; A<sub>p</sub>: amplitude of the fast VO<sub>2</sub> component; VO<sub>2</sub>: oxygen uptake; A<sub>sc</sub>: amplitude of the slow VO<sub>2</sub> component; [La<sup>-</sup>]<sub>peak</sub>: peak blood lactate; HR: heart rate; Aer: aerobic; AnL: anaerobic lactic; AnAL: anaerobic alactic; E<sub>tot</sub>: total energy expenditure; Ė: metabolic power; C: energy cost; BMI: Body Mass Index.

<sup>†</sup> significant time effect (p ≤ 0.05);

\* significant difference between E1 and E2, E1 and E3 or E1 and E4 (p ≤ 0.05);

# significant difference between E2 and E3 or E2 and E4 (p ≤ 0.05);

& significant difference between E3 and E4 (p ≤ 0.05).

**Table 2.** The beta coefficients ( $k$ ) identify the importance of each factor in the performance of 400-m test in front crawl (T400) at baseline and when using relative changes ( $\Delta$ ) after preparatory, specific and competitive period.

Training Period	Energetics										Technique					Anthropometrics				Constant
	MRT	A <sub>p</sub>	$\dot{V}O_2$	A <sub>sc</sub>	Lapeak	HR	Aer energy	AnL energy	AnAL energy	E <sub>tot</sub>	$\dot{E}$	C	SR	SL	SI	BMI	Height	Arm Span	Body Mass	
Baseline (E1)	-	-	-	0.06	-	-	-	-	-	-	-0.23	-	-0.74	-	-0.77	-	-	-0.09	0.05	716.92
Preparatory (E1-E2)	-	-	-	-	-	-	0.16	-0.10	-	-	-	-	-1.09	-	-0.78	-0.01	-	-0.07	-	-7.31
Specific (E2 to E3)	-	-	-	-	0.05	-	0.08	-	-	-	-	-	-0.64	-	-0.95	0.21	0.20	-	-	-3.855
Competitive (E3 to E4)	-	-	-	-	-	-	-	-0.36	-	-	0.01	-	-0.75	-	-1.18	-	-	0.24	-0.22	-2.617

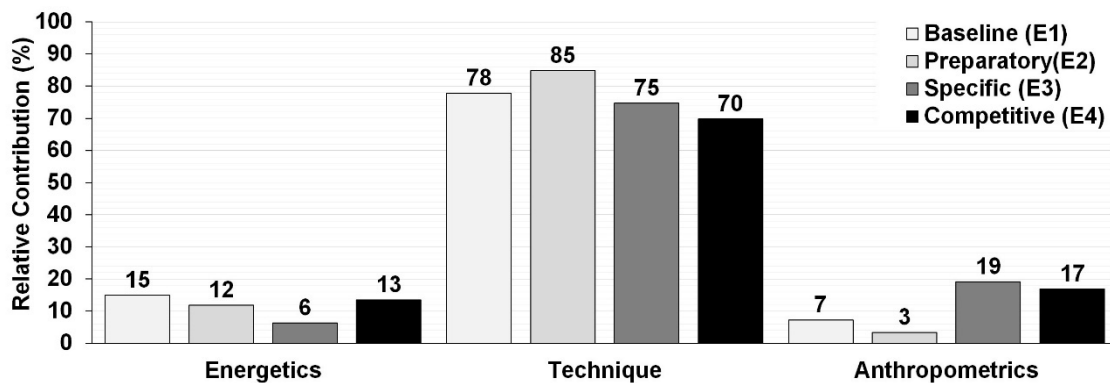
MRT: mean response time; A<sub>p</sub>: amplitude of the fast  $\dot{V}O_2$  component;  $\dot{V}O_2$ : oxygen uptake; A<sub>sc</sub>: amplitude of the slow  $\dot{V}O_2$  component; Aer: aerobic; AnL: anaerobic lactic; AnAL: anaerobic alactic; E<sub>tot</sub>: total energy expenditure;  $\dot{E}$ : metabolic power; C: energy cost; SR: stroke rate; SL: stroke length; SI: stroke index; BMI: Body Mass Index. “-”: excluded variable

**Table 3.** The percentage (%) of the contribution of each variable for the performance of 400-m test in front crawl (T400) at baseline and when using relative changes ( $\Delta$ ) after preparatory, specific and competitive period.

Training Period	Energetics										Technique					Anthropometrics			
	MRT	A <sub>p</sub>	$\dot{V}O_2$	A <sub>sc</sub>	Lapeak	HR	Aer energy	AnL energy	AnAL energy	E <sub>tot</sub>	$\dot{E}$	C	SR	SL	SI	BMI	Height	Arm Span	Body Mass
Baseline (E1)	-	-	-	3.1	-	-	-	-	-	-	11.9	-	38.2	-	39.6	-	-	4.7	2.5
Preparatory (E1-E2)	-	-	-	-	-	-	7.3	4.5	-	-	-	-	49.4	-	35.4	0.4	-	3.0	-
Specific (E2 to E3)	-	-	-	-	2.5	-	3.8	-	-	-	-	-	29.9	-	44.7	9.8	9.2	-	-
Competitive (E3 to E4)	-	-	-	-	-	-	-	13.0	-	-	0.4	-	27.2	-	42.6	-	-	8.6	8.3

MRT: mean response time; A<sub>p</sub>: amplitude of the fast  $\dot{V}O_2$  component;  $\dot{V}O_2$ : oxygen uptake; A<sub>sc</sub>: amplitude of the slow  $\dot{V}O_2$  component; Aer: aerobic; AnL: anaerobic lactic; AnAL: anaerobic alactic; E<sub>tot</sub>: total energy expenditure;  $\dot{E}$ : metabolic power; C: energy cost; SR: stroke rate; SL: stroke length; SI: stroke index; BMI: Body Mass Index. “-”: excluded variable

Technique showed the greatest influence over the macrocycle (preparatory: 85%; specific: 75%; competitive: 70%), primarily the SR and SI (Table 2, Table 3 and Fig. 2). Anthropometrics had a substantial influence at the specific (19%) and competitive training periods (17%), mainly the arm span (Table 2 and 3). Technique was the main contributor (77%) for changes in performance during the first macrocycle of the training season (E1 to E4) for these age-group swimmers, followed by anthropometrics (12%) and energetics (12%), respectively (Fig. 2).



**Fig 2.** The percentage contribution of energetics, technique and anthropometrics for the T400 swim performance at baseline and relative changes ( $\Delta$ ) during specific periods of a 16-week training cycle in age-group swimmers.

## DISCUSSION

Training stimulus and subsequent adaptation is a multi-factorial process where methodologies and stages in which training are presented to the swimmer can yield substantial differences in performance outcome. Studies on the interactive effects of technique, energetics and other performance-related areas are scarce in swimming. Changes and influence of energetics, technique and anthropometric were identified for age-group swimmers' performance of T400, where technique was the main contributor in the first macrocycle of traditional three-peak preparation program. Despite that, a powerful and endurable metabolic base cannot be ignored since the progressive evolution of the technique is closely linked to energetic improvements. Late to post pubertal age-group swimmers were sensitive to training stimulus, which reinforces the importance of being alert to the age and maturity of swimmers particularly during periods of growth.

Adjustments in volume and training load are employed by the swimming coach according to the established goal for each training period within a macrocycle. The aim is to develop specific energetical and technique outcomes at the main competition. Since training periodization is a dynamic process, dryland- or pool-based test sets, such as the T400 used here, are effective in understanding and controlling the swimmer's progress, identifying the main swimming performance determinants and their relationship with the training program. The current study was consistent with theoretical principles, providing a comprehensive biophysical overview of the main contributors to performance during the first 16-weeks macrocycle from a competitive season. Substantial changes observed for Aer energy contribution (increased by ~2%), SR (increased by ~13%) and improvements in performance and  $v$  by ~7% (Table 1) are consistent with a typical preparatory period program, which aims to improve general, biological, physical and technical skills to maximize metabolic and technical adaptations in preparation for future workloads (14,36,38). The Aer energy, SR and arm span were, respectively, the main contributors to changes in energetics, technique and anthropometrics. Changes in the performance of T400 were influenced by 12% from energetics during the preparatory period, with a remarkable influence of technique by 85% in these 14-15 years old swimmers. Thus, coaches should give priority to technical development of swimmers in this age-group while attending to the issues of fitness (energetics) and growth (anthropometrics).

The specific period is used to develop specific competitive skills while maintaining the general metabolic adaptations achieved at the end of preparatory period (14,36). The proportion of general conditioning work is reduced while skill-based conditioning workouts are increased (for instance, power sets), to emphasize technical and tactical preparation for the main swimming competition. A gradual improvement of physical and technical abilities is induced by increasing the training load. While changes in technique was the main contributor to changes in T400 performance in the specific period, the increase in anthropometrics influence was remarkable, indicating that the gain in performance of these 14-15 year-old age-group swimmers was also related to growth over 16 weeks. Likewise, SI was the best single contributor to improvements in the specific

training period, followed by SR and BMI. The mean BMI values are in agreement with the literature indicating that the swimmers body moved towards to the more hydrodynamic ectomorphic somatotype profile (15,41), but it is arguable whether swimmers were doing enough supervised strength training in the gym (38).

The aim of the training microcycle is for swimmers to reach peak performance at the end of this training period during the main competition. Although similar mean performance values were observed from specific to the competitive period, the mean performance and SR improved from baseline to the end of the competitive training period. An increase in the energetics and a modest decrease in the contribution of technique and growth to changes in T400 performance were evident from the specific to competitive training period. Clemente-Suarez et al. (2) observed trivial adaptations in energetics and technique after 10-weeks of traditional training periodization. However, the timing of pre and post-assessments within the training season were not specified, making it difficult to compare the results obtained in the present study. Papoti et al. (24) observed improved  $v$ , but not in the same proportion as force after competition period (taper, 11 days). We observed that technique was the main contributor during competition period. Improvements in  $v$  and performance have been observed with and without increase in  $\dot{V}O_{2max}$  (23). Regarding the present study, improvements in performance were observed without significant changes in  $\dot{V}O_{2max}$  and C when compared to baseline, but a higher metabolic power was observed (Table 1), which does not provide indirect support for the remarkable influence of technique in age-group swimmer development (23,35,41).

Perhaps the marked influence observed in SR, SL and SI for changes in T400 were more evident over the macrocycle since there is a close mathematical relationship between these variables (4,20). In fact, the product of SR and SL represents the  $v$ , and SI describes the swimmer's ability to move at a given  $v$  with the fewest number of strokes ( $v \cdot SL$ ). Despite that, the evidence of lower energetic contribution over the macrocycle may have been also influenced by the intra-/inter-subject variability and the degree of reliability in age-group testing protocols (20,26). Since performance has been improved, it was expected an increase in metabolic power or a decline in energy cost (41). In fact, although C has been increased (mainly due to increase in  $v$  and in hydrodynamic resistance related to

growth), a higher increase in  $\dot{V}O_2$  were evident after 16-weeks (Table 1). Although energetic and technique training load-adaptation pathways should be considered separately, the magnitude of changes in performance are dependent on the characteristics of the training programs. Thus, a progressive build-up aiming for a powerful and endurable metabolic base cannot be ignored since energetics are closely linked to technique (3,37). Planning and evaluation of age-group swimming program need to consider how energetics and technique can be developed in isolation and combination by prescription of training sets and drills. Progression of training load through the majority of the macrocycle was  $\sim 10\% \cdot \text{week}^{-1}$ , which confirms the specific recommendations (increasing load by increments of 5-10% per week) to prevent injuries (11,39) in athletes. In addition, the percentages of the individual maximal load observed within the macrocycle ( $\sim 29\%$  for taper,  $\sim 84\%$  for short-,  $\sim 91\%$  for medium- and  $\sim 77\%$  for long-term) are comparable to improvements in middle distance performance by senior swimmers (12). It is also important to recognize a limitation of the present study design. Swimmers should reach their best performances during the main competition of the macrocycle. In fact, this goal was achieved by  $\sim 83\%$  of the swimmers (20/24 swimmers). However, since the last evaluation (E4) could only be performed after the main competition, there may have been residual fatigue or possibly compromised motivation.

Even in swimming middle-distance events, the performance of competitive swimmers is closely matched. Besides, progressions in performance over a 12-month period leading up to the Olympic Games appear small, but in closely matched races they can have a substantial effect on the outcome (25). The 400-m freestyle is important for performance analysis in competitive swimming. Although many distances used in swimming competition does not exceed 2 min, the aerobic power training zone is relevant and can be assessed with a single T400. This protocol is widely used to assess aerobic fitness and training intensities prescription (18,40). The T400 was sufficiently sensitive to identify the main changes of each training period of the first macrocycle during a traditional three-peak preparation program.

In conclusion, improvements in technique had the biggest influence on performance of T400 in age-group swimmers' performance, supported by improvements in energetics (fitness) and underlying growth and physical maturation. These outcomes support the primary role of technique development in age-group swimmers as a consequence of effective planning and coaching throughout the 16-week training macrocycle.

### **PRACTICAL APPLICATIONS**

Although swimming technique was the greater contributor for changes in performance of T400 over the macrocycle, it is closely connected with energetics, thus a powerful and enduring metabolic base cannot be overlooked. It is important to be aware of the growth effects, since late to post pubertal age-group swimmers still are sensitive to training stimulus. Coaches and performance analysts should be aware that training periodization is a dynamic process, with a variable pattern of changes in key technical, energetic and anthropometric characteristics. Swimmers should be evaluated regularly by coaches and sports scientists over the training season.



## Chapter 6.

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### **Biophysical follow-up of age-group swimmers during a traditional three-peak preparation program**

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Submitted to The Journal of Strength and Conditioning Research

## **Abstract**

### Purpose

The aim of this study was to quantify changes and contributions of energetic, technique and anthropometric profiles across a traditional three-peak swimming season.

### Methods

Twenty-four age-group swimmers (11 boys  $14.7 \pm 0.8$ ; 13 girls  $14.3 \pm 0.6$  y) of equal maturational stage were monitored through a 400-m test in front crawl (T400). Energetic, technique and anthropometric characteristics were compared before and after macrocycle I, II and III. Gender interaction was verified only for amplitude of the fast oxygen uptake component and height (moderate). Multiple linear regressions and principal component analysis were used to identify the most influential variables and the relative contribution of each domain (energetics, technique and anthropometrics) to changes in swimming performance of T400.

### Results

The relative contributions for the performance of T400 after macrocycles I, II and III were respectively 6, 18, and 27% for energetics, 88, 69, and 54% for technique, and 6, 13 and 20% for anthropometrics. Technique was the biggest contributor (71%) for changes in the performance of T400 over the training season, followed by energetics (17%) and anthropometrics (12%).

### Conclusions

Technique played the main role during the competitive season, regardless of gradual increase in the influence of energetics and anthropometrics. Despite that, energetics and technique are closely connected, thus a powerful and endurable metabolic base and cannot be overlooked. Changes and influence of energetics, technique and anthropometric on age-group swimmers' performance over a traditional three-peak swimming season could be described by the T400 swimming test, providing a comprehensive biophysical overview of the main contributors to swimming performance.

**Key words:** Swimming; Periodization; Training season; Age-group; Physiology; Biomechanics; Anthropometry; Longitudinal

## Introduction

The performance in competitive swimming is determined by quite a lot of aspects. Fluctuations in energetics, technique and anthropometrics factors, associated with performance, provide important insights into a swimmer's preparation for competition. However, detailed information on parallel changes in these measures, and their relationship to swimming performance, are difficult to obtain in the aquatic environment (Morais et al. 2014). Conclusive information on the relationships between swimming determinant variables and performance during a training season cannot be provided by cross-sectional swimming-related studies. Therefore, longitudinal data on swimmers training are required.

The dynamic process of training periodization is a branch of training theory in the sports context, used to promote long- or short-term training and performance improvements. It is a design strategy that consist of preplanned, systematic variations in specificity, intensity, and volume prearranged in periods or cycles within an overall training program (Issurin 2010; Hellard et al. 2017). The multi-year preparation is the higher-level of the hierarchical periodized system, which is followed by the macrocycles. However, few data are available on the pattern of changes in key measures during a training season in age-group swimmers. Longitudinal studies in elite swimmers showed that changes in immunological, psychological, hormonal, hematological and other physiological variables are reliant on training stimuli (Santhiago et al. 2009; Santhiago et al. 2011; Morgado et al. 2018), but the relationship between these areas and fluctuation (s) in performance has not always been described. Likewise, cardiac morphology and performance are reliant on anthropometrics and training in age-group swimmers (Ayabakan et al. 2006; Csajagi et al. 2015; Kavouras et al. 1996).

Swimming performance during a competitive event relies on the conversion of metabolic into mechanical power through a given energetic efficiency (Figueiredo et al. 2013). The total energy expenditure ( $E_{tot}$ ), which is the sum of aerobic (Aer), anaerobic lactic (AnL) and anaerobic alactic (AnAL) energy contributions, the respective metabolic power ( $\dot{E}$ ) and the energy cost (C; the energy consumed to cover one unit of distance while swimming at a given speed), have been estimated through indirect calorimetry during different swimming events (Sousa

et al. 2013). It is well reported that these methods are practical and robust to implement in routine testing for both junior and senior swimmers.

The oxygen uptake ( $\dot{V}O_2$ ) and blood lactate concentrations ( $[La^-]$ ) for a given swimming effort can change during a typical training season in responses to the administration of volume, intensities and loads by the coach. For instance, maximal oxygen uptake ( $\dot{V}O_{2max}$ ) is a traditionally reported physiological parameter of aerobic function. The analysis of the dynamic  $\dot{V}O_2$  response following the onset of exercise ( $\dot{V}O_2$  kinetics) provide a detailed picture about the energetic-related determinants to swimming performance (Reis et al. 2012). However, no study has yet quantified  $\dot{V}O_2$  kinetics over a training season in age-group swimmers. It is plausible that substantial changes in  $\dot{V}O_2$  related parameters,  $E_{tot}$ ,  $\dot{E}$  and  $C$  can be seen in parallel with improvements in performance during a competitive season in age-group swimmers.

Fluctuations in an anthropometric profile may influence technique, which affects energetics and thus swimming performance (Sammoud et al. 2018). Energetics, technique and anthropometrics are closely related with swimming performance (Lätt et al. 2010), thus it is important for coaches to well understand the relationship among these areas with the training employed over a training season. Thus, the aim of this study was to identify changes in energetics, technique and anthropometric profile while following age-group swimmers over a training season through a traditional three-peak preparation program. Linking changes between these profiles, and identifying their relative contributions to performance, will inform the evaluation and prescription of age-group swimming training programs.

## **Methods**

### **Experimental Approach to the Problem**

A single-group prospective study was conducted, and swimmers were tested during a traditional three-peak preparation program (one competitive season), before (E1) and after the first (E2), second (E3) and third (E4) macrocycle. Repeated measures of performance-related physiological, biomechanical and anthropometric variables were obtained. The first experimental testing (E1) took place at the first week of the first macrocycle. The second (E2), third (E4), and

last (E4) experimental testing were conducted, respectively, until 48 h after the main competition of the macrocycle I, II and III.

Pubertal maturation stage was assessed prior to the first experiment and anthropometric variables were measured in all testing sessions. The experimental testing took place in a 25-m indoor pool with a mean water temperature of 27.5°C, air temperature 25.4°C, and relative humidity 66%. After an ~800-m moderate intensity front crawl warm-up, swimmers performed a 400-m maximal effort front crawl swim test (T400) for performance, physiological and biomechanical assessment. The T400 was chosen given its validity and utility for assessing aerobic power in age-group swimmers (Smith et al. 2002; Zacca et al. 2017). All participants avoided vigorous exercise in the previous 24 h, were well-hydrated, abstained from caffeine for at least 3 h before testing and encouraged verbally during the T400.

### **Participants**

Twenty-four late to post pubertal age-group swimmers, 11 boys and 13 girls (14.7 ± 0.8 and 14.3 ± 0.6 y, respectively), volunteered to take part in the current study. Swimmers had over 5 y of competitive experience and trained six to seven swimming sessions and two to three hours of dryland training per week in the same squad and under direction of the same coach.

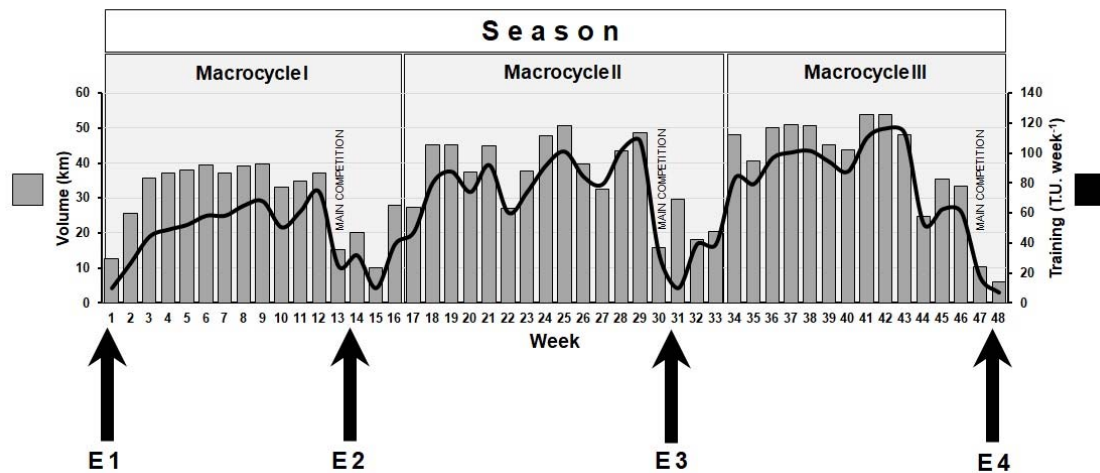
### **Study design**

This single-group prospective study followed a longitudinal design. Swimmers parents were informed about the benefits and risks of taking part in the current study prior to signing an informed consent form, which was approved by the ethics board of the local university and performed according to the Helsinki Declaration.

### **Procedures**

Standard methodologies were used to quantify the swimming training workload (Mujika et al. 1996). Swimming and dry land training (mainly strength and power training sessions) were categorized in different training zones. Swimming distance values were multiplied by the intensity factor and totalled. The magnitude of the load was expressed in arbitrary training units (T.U.), quantified from the calculated sum of the volumes swam in each of the zones, multiplied by the respective intensity factor, and the total volume effectively completed. Dry

land training activities were quantified by time and converted to swimming distance (Mujika et al. 1996). The swimmers' T.U. and volume were monitored during a 48-weeks. Fig. 1 summarizes the training volume and load (T.U.) over the 48-weeks training season.



**Fig. 1** Weekly training load for the entire group of swimmers during the 48-weeks of the training season. Values of volume and load are in km and T.U. (training unit), respectively.

An anthropometric profile (body mass, height, arm span and body mass index, BMI) was obtained by an International Society for the Advancement of Kinanthropometry accredited level I anthropometrist. Maturational status was verified by a valid and reliable self-assessment of secondary sexual characteristics (Tanner and Whitehouse 1976).

Respiratory and pulmonary gas-exchange data were measured breath-by-breath using a telemetric portable gas analyzer (K4b<sup>2</sup>, Cosmed, Rome, Italy) connected to a low hydrodynamic resistance respiratory snorkel and valve system (AquaTrainer®, Cosmed, Rome, Italy; Ribeiro et al., 2016). The telemetric portable gas analyzer was calibrated before each testing session and transported along the swimming pool suspended at a 2-m height over the water on a steel cable (de Jesus et al. 2014). Swimmers were familiarised during three months before the first testing, three times per week, with a snorkel (Arena swim snorkel SKU: 95257; Tolentino, Italy) and nose clip (Arena nose clip pro SKU: 95204; Tolentino, Italy). In-water starts and open turns were employed given the physical restrictions associated with the equipment (Ribeiro et al. 2016). Heart rate (HR)

was monitored continuously by a Polar Vantage NV (Polar Electro Oy, Kempele, Finland) that transmitted the data telemetrically to the K4b<sup>2</sup> portable unit. Capillary blood samples for [La<sup>-</sup>] were collected from an earlobe before exercise and immediately after the T400 at the first, third, fifth and seventh min of the recovery period ([La<sup>-</sup>]<sub>peak</sub>; Lactate Pro analyzer, Arkray, Inc, Kyoto, Japan).

The first 20 s of  $\dot{V}O_2$  data after the onset of exercise (the cardiodynamic phase of the  $\dot{V}O_2$  response) were not considered for  $\dot{V}O_2$  kinetics analysis, and errant breaths were omitted by only including those within  $\dot{V}O_2$  local mean  $\pm$  4SD (Sousa et al. 2014). Subsequently, individual breath-by-breath  $\dot{V}O_2$  responses were time averaged every 10 s and smoothed using a 3-breath moving average (de Jesus et al. 2014). Since the inherent breath-by-breath noise observed in young swimmer's response profiles could mask any clear changes in ventilatory variables (Fawkner and Armstrong 2004), the on-transient during the T400 was modelled for each swimmer using the mono exponential model described in Equation 1:

$$\dot{V}O_2(t) = A_0 + H(t - TD_p) \cdot A_p (1 - e^{-(t - TD_p)/\tau_p}) \quad (1)$$

where  $\dot{V}O_2(t)$  represents the relative  $\dot{V}O_2$  at the time  $t$ ,  $A_0$  is the  $\dot{V}O_2$  at rest (average from the last 2 min previous to exercise),  $H$  represents the Heaviside step function (Equation 2; Ma et al. 2010) and  $A_p$ ,  $TD_p$  and  $\tau_p$  are the amplitude, time delay and time constant of the fast  $\dot{V}O_2$  component.

$$H(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases} \quad (2)$$

Bootstrapping with 1000 samples was used to estimate  $\dot{V}O_2$  kinetics parameters. The mean response time (MRT) was obtained as  $TD_p + \tau_p$  and  $\dot{V}O_{2max}$  computed as the mean  $\dot{V}O_2$  over the last 60 s of the T400 (Hanon et al. 2008; Ingham et al. 2013; Zacca et al. 2017). The amplitude of the slow  $\dot{V}O_2$  component ( $A_{sc}$ ) was estimated as the difference between the  $\dot{V}O_2$  at the end (average of the last 60 s) and  $A_p + A_0$ .

The  $E_{tot}$  was estimated as the sum of  $A_{er}$ ,  $A_{nL}$  and  $A_{nAL}$  energy contributions, with the  $A_{er}$  and  $A_{nL}$  energy calculated from the time integral of the net  $\dot{V}O_2$  versus time relationship and using the Equation 3, respectively (Sousa et al. 2014):

$$\text{AnL} = [\text{La}^-]_{\text{net}} \cdot \beta \cdot M \quad (3)$$

where  $[\text{La}^-]_{\text{net}}$  is the difference between the  $[\text{La}^-]$  before and after exercise ( $[\text{La}^-]_{\text{peak}}$ ),  $\beta$  is the constant for  $\text{O}_2$  equivalent of  $[\text{La}^-]_{\text{net}}$  ( $2.7 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{mM}^{-1}$ ) and  $M$  is the body mass of the swimmer (Zamparo et al. 2011). These energy contributions were then expressed in kJ assuming an energy equivalent of  $20.9 \text{ kJ} \cdot \text{L}^{-1}$  (Zamparo et al. 2011). The AnAL energy was estimated from the maximal phosphocreatine (PCr) splitting in the contracting muscle (Equation 4; Sousa et al. 2014):

$$\text{AnAL} = \text{PCr} \cdot (1 - e^{-t/\tau}) \cdot M \quad (4)$$

where PCr is the phosphocreatine concentration at rest,  $t$  is the exercise time,  $\tau$  is time constant of the PCr splitting at exercise onset (23.4 s) and  $M$  is the body mass. Subsequently, AnAL was expressed in kJ by assuming an energy equivalent of  $0.468 \text{ kJ} \cdot \text{mM}^{-1}$  and a phosphate/oxygen ratio of 6.25 (Zamparo et al. 2011). The  $C$  was obtained as the ratio between  $E_{\text{tot}}$  and distance, and  $\dot{E}$  (kW) was estimated as the ratio between  $E_{\text{tot}}$  and performance (s) of T400 (Zamparo et al. 2011).

Surface and underwater video cameras (50 Hz, Sony® Handycam HDR-CX130, Japan) recorded 10-m of the last 25-m of each 100-m interval (within two points at 7.5 m from each end of the swimming-pool to exclude the influence of the turning phase). Cameras were synchronised with Adobe Premiere Pro CC (v2015, Adobe Systems, San Jose, California, USA) through a light flash activated prior to each trial. The  $v$  from each 100-m interval was measured from the time to cover the middle 10-m of each length ( $v = d/t_{10}$ , where  $d = 10 \text{ m}$  and  $t_{10} = \text{time for the } 10 \text{ m}$ ) and the  $v$  of T400 was calculated as the mean of the four 100-m intervals. Stroke rate (SR) was computed from the time taken to complete three consecutive upper limbs cycles. Stroke length (SL) calculated from the ratio between  $v$  and corresponding SR, and stroke index (SI), a measure of swimming efficiency, calculated by multiplying  $v$  by SL (Costill et al. 1985).

### Statistical Analysis

Mean and standard deviation (SD) are presented as descriptive statistics. The Shapiro–Wilk test was used to test normality of the data. One-way ANOVA (using gender as covariate) and Bonferroni post hoc tests were used to analyse



differences between each variable along at baseline (E1) and after (using delta values) macrocycle I (E2), macrocycle II (E3) macrocycle III (E4). Eta squared ( $\eta^2$ ) test was used to quantify the percentage of the variance explained by each covariate (effect size) and interpreted as follows:  $0 < \eta^2 < 0.04$  trivial effect,  $0.04 \leq \eta^2 \leq 0.24$  small,  $0.25 \leq \eta^2 < 0.64$  moderate and  $\eta^2 \geq 0.64$  large effect (Ferguson 2009).

Principal component analysis was used as the method of extraction (scree plot criterion) to reduce the initial set of variables at each area (energetics: MRT,  $A_p$ ,  $\dot{V}O_2$ ,  $A_{sc}$ ,  $[La]_{peak}$ , HR, Aer, AnL, AnAL,  $\dot{E}$ ,  $E_{tot}$  and C; technique: SR, SL and SI; anthropometrics: BMI, height, arm span and body mass) from E1, E2, E3 and E4, while removing the effect of multicollinearity. Then, multiple linear regressions (“Enter” method) were applied to identify the most influential variables and the relative contribution of energetics, technique and anthropometrics to swimming performance (s) of T400 at baseline (E1) and after (using delta values) each macrocycle. These regression analyses were not intended to predict T400 performance, but to determine the influence of energetics, technique and anthropometric performance-related variables during each macrocycle of a traditional three-peak preparation program (one competitive season) (Figueiredo et al. 2013). Statistical significance was set at  $\alpha = 0.05$ . Data were recorded and analysed using SPSS, version 24 (SPSS Inc, Chicago, Ill, USA).

## Results

Gender interaction was observed only for amplitude of the  $A_p$  ( $F = 4.05$ ;  $p = 0.01$ ;  $\eta^2 = 0.34$  “moderate effect”; observed power = 0.78) and height ( $F = 3.95$ ;  $p = 0.02$ ;  $\eta^2 = 0.33$  “moderate effect”; observed power = 0.76). Thus, male and female swimmers data were pooled and analysed as a single group. The mean training load per week ( $T.U. \cdot week^{-1}$ ) for each macrocycle was:  $61 \pm 19$  (macrocycle I),  $73 \pm 27$  (macrocycle II) and  $84 \pm 27$  (macrocycle III). The mean volume per week ( $km \cdot week^{-1}$ ) for each macrocycle was:  $33 \pm 9$  (macrocycle I),  $37 \pm 11$  (macrocycle II) and  $42 \pm 12$  (macrocycle III) (not accounting for transition periods). Progression of volume ( $\% \cdot week^{-1}$ ) and training load until two weeks prior to the main competition of each macrocycle were, respectively: macrocycle I ( $\sim 4.3$  and  $\sim 10.5$ ), macrocycle II ( $\sim 6.1$  and  $\sim 8.7$ ) and macrocycle III ( $\sim 8.4$  and  $\sim 8.6$ ).

## Changes in technique, energetics and anthropometrics across the training season

The comparison of technique, energetics and anthropometrics variables along each macrocycle are presented in Table 1. Improvements in 400-m time trial performance and SR occurred mainly in the first macrocycle of the training season (performance: -10 %; 95%CI -15 to -5%;  $p < 0.001$ ; SR: 12.5%; 95%CI 4.9 to 20.8%;  $p = 0.002$ ). The SI increased  $\sim 11\%$  (95%CI 2 to 18%;  $p = 0.01$ ) in the second macrocycle compared to the beginning of the training season, and then remained similar across the third macrocycle. Regarding the Energetics domain, MRT in the macrocycle II was higher than in macrocycle I (35 %; 95%CI 15 to 56%;  $p = 0.001$ ). Despite that, the Ap increased from the beginning of the training season to macrocycle II (22%; 95%CI 2 to 43%;  $p = 0.03$ ) and III (30 %; 95%CI 7 to 52 %;  $p = 0.01$ ), and from macrocycle I to macrocycle III (17%; 95%CI 1 to 33%;  $p = 0.038$ ). The mean values of  $\dot{V}O_{2\max}$  increased from the beginning of the training season to end of macrocycle I (13%; 95%CI 2 to 25%;  $p = 0.024$ ), II (19%; 95%CI 8 to 30%;  $p = 0.002$ ) and III (23%; 95%CI 14 to 33%;  $p < 0.001$ ), but remaining relatively similar between macrocycle I and II, and between macrocycle II and III. Significant increase in Aer energy (47kJ; 95%CI 9 to 84kJ;  $p = 0.015$ ),  $E_{\text{tot}}$  (47kJ; 95%CI 4 to 90kJ;  $p = 0.029$ ),  $\dot{E}$  (0.26 kW; 95%CI 0.14 to 0.38 kW;  $p < 0.001$ ) and C (0.11 kJ·m<sup>-1</sup>; 95%CI 0.01 to 0.22 kJ·m<sup>-1</sup>;  $p = 0.029$ ) were observed from baseline to the end of the training season. The mean Aer energy has been increased from macrocycle II to III (30kJ; 95%CI 0 to 59kJ;  $p = 0.047$ ). A significant increase in  $\dot{E}$  has been also observed from baseline to preparatory (0.15 kW; 95%CI 0.03 to 0.26 kW;  $p = 0.012$ ) and specific (0.21 kW; 95%CI 0.10 to 0.32 kW;  $p = 0.001$ ) training periods, and from preparatory to the end of competitive period (0.11 kW; 95%CI 0.01 to 0.21 kW;  $p = 0.033$ ). Other energetical variables remained similar across the training season. Regarding anthropometrics, height increased from the beginning of the training season to macrocycle I (1.5 cm; 95%CI 0.7 to 2.4 cm;  $p = 0.002$ ) and macrocycle III (2.1 cm; 95%CI 1.1 to 3.1 cm;  $p = 0.001$ ). Mean values of arm span has also increased between base line and macrocycle I (1.4 cm; 95%CI 0.5 to 2.2 cm;  $p = 0.004$ ), macrocycle II (1.5 cm; 95%CI 0.5 to 2.6 cm;  $p = 0.006$ ) and macrocycle III (1.8

cm; 95%CI 0.5 to 3.1 cm;  $p = 0.007$ . Mean values for Body mass and BMI remained relatively similar across the training season.

### **Relative contributions to swimming performance**

The beta coefficients for the selected variables are presented in Table 2. Each coefficient represents the underlying contribution to the performance of T400 at baseline (E1) and changes ( $\Delta$ ) in performance each macrocycle. The variation in performance explained during the macrocycles ranged from 58-92%. Adjusted  $R^2$  for the selected variables models were 0.91 ( $P < 0.01$ ) for baseline, 0.64 ( $P = 0.08$ ) for E2 macrocycle I, 0.99 ( $P < 0.01$ ) for macrocycle II and 0.77 ( $P = 0.055$ ) for macrocycle III.

**Table 1.** Data variation (time effect; one-way ANOVA) and changes in technique, energetics and anthropometrics variables in response to a 400-m test in front crawl (T400) performed by all swimmers over the training season.

	Time effect				Baseline (E1)		Macrocycle I (E2)			Macrocycle II (E3)			Macrocycle III (E4)		
	F	p-value	Eta <sup>2</sup>	Power	Mean	±SD	Mean	±SD	Δ (%) E1vsE2	Mean	±SD	Δ (%) E2vsE3	Mean	±SD	Δ (%) E3vsE4
<b>TECHNIQUE</b>															
Performance (s)	20.75	0.00 <sup>†</sup>	0.72	1.00	356	20	322*	20	-9.5	318*	18	-1.3	322*	24	1.2
v (m·s <sup>-1</sup> )	16.03	0.00 <sup>†</sup>	0.67	1.00	1.08	0.06	1.18*	0.07	9.1	1.21*	0.06	2.6	1.18*	0.10	-2.5
SR (cycles·min <sup>-1</sup> )	16.14	0.00 <sup>†</sup>	0.67	1.00	30.2	2.5	34.1*	2.5	12.9	34.2*	1.7	0.3	33.8*	2.4	-1.2
SL (m)	1.97	0.14 <sup>†</sup>	0.20	0.44	2.16	0.19	2.08	0.16	-3.6	2.13	0.13	2.4	2.10	0.16	-1.6
SI (m <sup>2</sup> ·s <sup>-1</sup> )	2.99	0.05 <sup>†</sup>	0.27	0.63	2.35	0.27	2.47	0.30	5.1	2.59*	0.26	4.9	2.50	0.37	-3.7
<b>ENERGETICS</b>															
MRT (s)	1.19	0.33	0.13	0.28	43.7	23.2	28.7	7.2	-34.4	38.9#	9.4	35.6	33.5	12.1	-14.0
A <sub>p</sub> (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	11.73	0.00 <sup>†</sup>	0.59	0.99	34.7	5.5	38.6	6.9	11.2	42.5*	10.2	10.2	45.1*#	8.7	6.1
VO <sub>2</sub> (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	16.49	0.00 <sup>†</sup>	0.67	1.00	43.3	7.5	49.2*	6.9	13.7	51.6*	8.8	4.9	53.5*	8.8	3.7
A <sub>sc</sub> (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	2.25	0.09	0.09	0.55	2.09	1.89	2.56	1.02	22.7	2.19	1.02	-14.5	2.82	1.94	28.6
[La <sup>-</sup> ] <sub>peak</sub> (mmol·L <sup>-1</sup> )	0.73	0.54	0.08	0.18	6.3	2.6	5.3	1.5	-14.9	6.8	1.6	28.1	6.2	1.9	-8.8
HR (bpm)	0.65	0.59	0.08	0.16	182	5	184	8	0.9	184	9	0.1	185	5	0.7
Aer energy (kJ)	5.76	0.00 <sup>†</sup>	0.42	0.91	295	65	312	53	5.8	321	60	3.0	342*#	61	6.4
AnL energy (kJ)	0.58	0.63	0.07	0.15	17.3	9.5	15.1	5.8	-12.6	19.6	7.0	29.5	17.4	6.6	-10.8
AnAL energy (kJ)	0.13	0.93	0.08	0.07	26.1	4.9	26.5	4.3	1.4	26.3	3.7	-0.80	26.5	3.6	0.8
Aer contribution (%)	0.68	0.57	0.08	0.17	87.2	2.3	88.2	1.5	1.1	87.4	2.1	-0.9	88.6	1.8	1.4
AnL contribution (%)	0.33	0.80	0.04	0.10	4.9	2.3	4.2	1.3	-14.2	5.4	1.6	28.4	4.4	1.4	-18.5
AnAL contribution (%)	2.99	0.51	0.27	0.63	7.9	1.2	7.6	1.0	-3.8	7.3	1.1	-3.9	7.0	0.9	-4.1
E <sub>tot</sub> (kJ)	5.35	0.00 <sup>†</sup>	0.40	0.89	338	74	354	60	4.5	367	64	3.8	385*	68	5.1
Ė (kW)	23.28	0.00 <sup>†</sup>	0.74	1.00	0.95	0.22	1.10*	0.22	15.7	1.17*	0.25	6.3	1.22*#	0.28	4.3
C (kJ·m <sup>-1</sup> )	5.35	0.00 <sup>†</sup>	0.40	0.89	0.85	0.18	0.88	0.15	4.5	0.92	0.16	3.9	0.96*	0.17	5.0
<b>ANTHROPOMETRICS</b>															
Height (cm)	25.09	0.00 <sup>†</sup>	0.76	1.00	167	6	168	7	0.5	169*	7	0.4	169*	7	0.3
Body mass (kg)	0.21	0.88	0.03	0.08	62.7	11.8	62.6	9.3	-0.2	63.1	8.9	0.78	63.6	8.8	0.8
Arm Span (cm)	16.52	0.00 <sup>†</sup>	0.67	1.00	172	10	173*	9	0.8	174*	9	0.12	174*	9	0.2
BMI	0.53	0.48	0.06	0.10	22.3	3.2	22.1	2.1	-1.0	22.0	1.8	-0.1	22.0	1.8	0.1

v: swimming speed; SR: stroke rate; SL: stroke length; SI: stroke index; MRT: mean response time; A<sub>p</sub>: amplitude of the fast VO<sub>2</sub> component; VO<sub>2</sub>: oxygen uptake; A<sub>sc</sub>: amplitude of the slow VO<sub>2</sub> component; [La<sup>-</sup>]<sub>peak</sub>: peak blood lactate; HR: heart rate; Aer: aerobic; AnL: anaerobic lactic; AnAL: anaerobic alactic; E<sub>tot</sub>: total energy expenditure; Ė: metabolic power; C: energy cost; BMI: Body Mass Index.

† significant time effect (p ≤ 0.05);

\* significant difference between E1 and E2, E1 and E3 or E1 and E4 (p ≤ 0.05);

# significant difference between E2 and E3 or E2 and E4 (p ≤ 0.05).

**Table 2.** The beta coefficients (*k*) identify the importance of each factor in the performance of 400-m test in front crawl (T400) at baseline and when using relative changes ( $\Delta$ ) after macrocycle I, II, and III.

Training Period	Energetics										Technique					Anthropometrics			Constant	
	MRT	A <sub>p</sub>	$\dot{V}O_2$	A <sub>sc</sub>	[La <sup>-</sup> ] <sub>peak</sub>	HR	Aer energy	AnL energy	AnAL energy	E <sub>tot</sub>	$\dot{E}$	C	SR	SL	SI	BMI	Height	Arm Span		Body Mass
Baseline (E1)	-	-	0.09	-	-	-	-	-	-	-	-0.27	-	-0.72	-	-0.74	-	-	-0.09	0.08	701.2
Macrocycle I (E1 to E2)	-	-	-	-	-	-	-	-	0.09	0.07	-	-	-1.54	-0.98	-	-	0.07	-	0.111	-17.2
Macrocycle II (E2 to E3)	-	-	-	-	-	-	-	0.16	-	0.30	-	-	-0.91	-	-0.85	-	0.26	-	-0.072	-9.4
Macrocycle III (E3 to E4)	-	-	-	-	-0.11	-	0.24	-	-	-	-	-	-0.42	-	-0.28	-	-0.16	-	0.096	-0.8

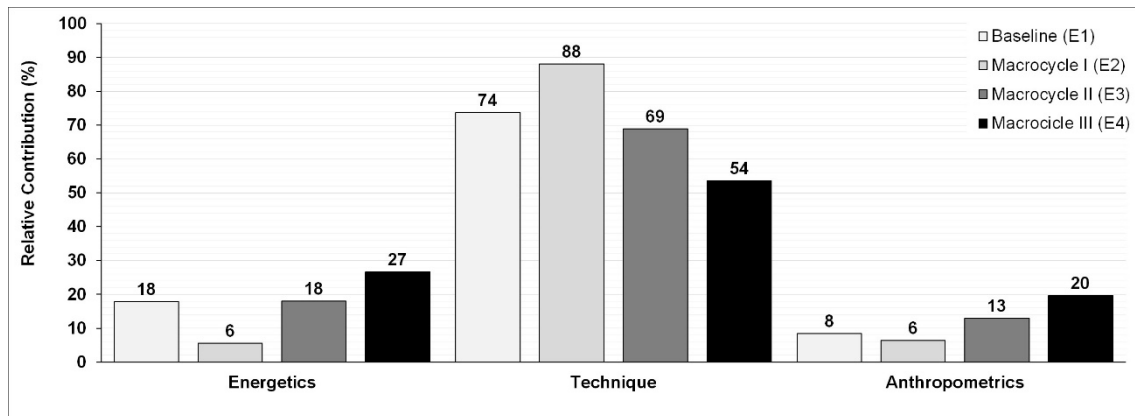
MRT: mean response time; A<sub>p</sub>: amplitude of the fast  $\dot{V}O_2$  component;  $\dot{V}O_2$ : oxygen uptake; A<sub>sc</sub>: amplitude of the slow  $\dot{V}O_2$  component; Aer: aerobic; AnL: anaerobic lactic; AnAL: anaerobic alactic; E<sub>tot</sub>: total energy expenditure;  $\dot{E}$ : metabolic power; C: energy cost; SR: stroke rate; SL: stroke length; SI: stroke index; BMI: Body Mass Index. “-”: excluded variable

**Table 3.** The percentage (%) of the contribution of each variable for the performance of 400-m test in front crawl (T400) at baseline and when using relative changes ( $\Delta$ ) after macrocycle I, II and III.

Training Period	Energetics										Technique					Anthropometrics			Body Mass
	MRT	A <sub>p</sub>	$\dot{V}O_2$	A <sub>sc</sub>	[La <sup>-</sup> ] <sub>peak</sub>	HR	Aer energy	AnL energy	AnAL energy	E <sub>tot</sub>	$\dot{E}$	C	SR	SL	SI	BMI	Height	Arm Span	
Baseline (E1)	-	-	4.4	-	-	-	-	-	-	-	13.5	-	36.3	-	37.4	-	-	4.5	3.9
Macrocycle I (E1 to E2)	-	-	-	-	-	-	-	-	3.2	2.4	-	-	53.9	34.1	-	-	2.5	-	3.9
Macrocycle II (E2 to E3)	-	-	-	-	-	-	-	6.3	-	11.7	-	-	35.7	-	33.2	-	10.2	-	2.8
Macrocycle III (E3 to E4)	-	-	-	-	8.3	-	18.4	-	-	-	-	-	32.5	-	21.1	-	12.3	-	7.4

MRT: mean response time; A<sub>p</sub>: amplitude of the fast  $\dot{V}O_2$  component;  $\dot{V}O_2$ : oxygen uptake; A<sub>sc</sub>: amplitude of the slow  $\dot{V}O_2$  component; Aer: aerobic; AnL: anaerobic lactic; AnAL: anaerobic alactic; E<sub>tot</sub>: total energy expenditure;  $\dot{E}$ : metabolic power; C: energy cost; SR: stroke rate; SL: stroke length; SI: stroke index; BMI: Body Mass Index. “-”: excluded variable

Technique showed the greatest influence over the season (macrocycle I: 88%; macrocycle II: 69%; macrocycle III: 54%), mainly the SR and SI (Table 2, Table 3 and Fig. 2). Anthropometrics had a substantial influence at the second (13%) and third macrocycle (20%), mainly height and body mass (Table 2 and 3). Technique was the main contributor (71%) for changes in performance during the training season (E1 to E4) for these age-group swimmers, followed by energetics (17%) and anthropometrics (12%), respectively (Fig. 2).



**Fig. 2** The percentage of the contributions of energetics, technique and anthropometrics for the T400 swim performance at baseline and relative changes ( $\Delta$ ) after each macrocycle of a 48-week training season in age-group swimmers.

## Discussion

Training stimulus and subsequent adaptation is a multi-factorial process where methodologies and periods in which training are offered to the swimmer can yield substantial differences in performance outcome. Thus, understanding the relationship between performance-related areas provide valuable data for coaches. However, studies on the interactive effects of technique, energetics and other performance-related areas are scarce in swimming. This is a rare study in which variables and parameters from breath-by breath  $\dot{V}O_2$  assessment in age-group swimmers were analysed on parallel with technique and anthropometrics during a traditional three-peak preparation program. In fact, direct  $\dot{V}O_2$  assessment in swimming during a training season was an arduous task, which gives value to the results of the current study. Changes and influence of energetics, technique and anthropometric were identified for age-group swimmers' performance of T400, in which technique was the main contributor during a competitive season. Despite that, a powerful and tolerable metabolic

base cannot be ignored since the progressive development of swimming technique is closely linked to energetic enhancements. Late to post pubertal age-group swimmers were sensitive to training stimulus, which underpins the importance of being aware to the age and maturity of swimmers particularly during growing periods.

Swimming coaches adjust volume and training load according to an established goal for each training period. The intention is to build-up performance-related energetical and technique outcomes until the main competition. It is important to keep in mind that training periodization is a dynamic process. In this sense, dryland- or pool-based test sets, such as the T400 applied here, are reliable in understanding and monitoring the swimmer's progress, identifying the main swimming performance factors and their relationship with the training program. Our study is in agreement with theoretical principles, providing a biophysical overview of the main contributors to performance during the 48-weeks training season. The main improvements for performance of T400 and SR (improved by ~11 and ~10% over the season) occurred in the first macrocycle, but changes in SI (improved by ~10% over the season) were evident only from the second macrocycle.

In terms of  $\dot{V}O_2$  kinetics, the MRT has increased from macrocycle I to macrocycle II, but increments in the  $A_p$  (increased by ~30% over the season) were evident from the second macrocycle onwards. In addition,  $\dot{V}O_{2max}$  (increased by ~23%), Aer energy (increased by ~16%),  $E_{tot}$  (increased by ~14%),  $\dot{E}$  (increased by ~28%) and C (increased by ~13%) were higher after a 48-weeks traditional three-peak preparation program. Despite that, Aer, AnL and AnAL percentage contributions to T400 remained similar over the training season. These results are consistent with a typical training season program, where progressive metabolic and technical adaptations are necessary in every macrocycle for future workloads (Issurin 2010; Tuner 2011; Vorontsov 2011). The SR, SI, Aer energy pathway,  $E_{tot}$ , height and body mass were, respectively, the two main contributors to changes in technique, energetics and anthropometrics. Changes in the performance of T400 during the training season were influenced, respectively, by 17% and 12% from energetics and anthropometrics, with a remarkable influence of technique by 71% in these age-group swimmers. Thus,

coaches should give priority to technical development while attending to the issues of fitness (energetics) and growth (anthropometrics) in age-group swimmers.

It is plausible that the marked influence observed in SR, SI and SL to changes in T400 were more evident over the training season since there is a close mathematical relationship between these variables (Costill et al. 1985; Morais et al. 2014). In fact, the product of SR and SL represents the  $v$ , and SI describes the swimmer's ability to move at a given  $v$  with the fewest number of strokes ( $v \cdot SL$ ). Besides, the evidence of lower energetic contribution over the training season may have been also affected by the intra-/inter-subject variability and the degree of reliability in age-group testing protocols (Capelli 1999; Reis et al. 2012; Morais et al. 2014). Despite that, changes in  $C$  (mainly due to increase in  $v$  and in hydrodynamic resistance related to growth) and  $\dot{E}$  were evident after 48-weeks (Zamparo et al. 2011). Technique variables seem to be more influential when inserted into regression analysis, which was more evident when using the delta values for each macrocycle during the follow-up, i.e., even with small variations in performance over time, technique variables are still sensitive to explain swimming performance enhancement. On the other hand, although small changes in performance are also associated with changes in some metabolic variables, these are not expressive enough to show a consistent influence of energetics in swimming performance improvement. Besides the high within-group variability observed by Capelli (1999), the results from our longitudinal experiment are consistent with the results obtained by a theoretical model used to quantify the role of  $C$ , maximal aerobic power and anaerobic energy stores when determining performance times of front crawl swimmers (Capelli 1999). Recently, a biophysical experiment performed with swimmers to better understand the factors associated with front-crawl performance at  $v\dot{V}O_{2max}$ , suggested that technique and  $\dot{E}$  are not performance determinants at this intensity (Ribeiro et al. 2017). However, useful power to overcome drag forces and performance efficiency (ratio between useful power to overcome drag and  $\dot{E}$ ) explained most of the variance in swimming performance at  $v\dot{V}O_{2max}$  (Ribeiro et al. 2017). Thus, even though energetic and technique training load-adaptation pathways should be considered separately, the magnitude of fluctuations in



performance are reliant on the characteristics of the training programs. A progressive build-up, aiming for a powerful and enduring metabolic base, cannot be ignored, since energetics are closely linked to technique (Costa et al. 2012; Vanrenterghem et al. 2017). Planning and monitoring of age-group swimming plans need to consider how energetics and technique can be developed in isolation and combination by prescription of training workouts.

Training periodization is a dynamic process where coaches should make, whenever necessary, changes to their training programs based on their potential capacities to help swimmers to improve (McKay et al. 2016; Vanrenterghem et al. 2017). Thus, understanding the inverse relationship between intensity and volume is mandatory when prescribing the amount of work and type of work during a training season periodization – i.e., as the volume increases, the intensity of the work should have a planned decrease. Swimmers cannot support a high intensity over a high volume of work for prolonged periods, so coaches must adjust it appropriately. Therefore, age-group swimmers can only have a high intensity, a high volume, or moderate amounts of both. Dryland- or pool-based test sets are typically applied to understand and control the swimmer's progression over the training season. However, energetics, technique and anthropometrics are typically not explored together in longitudinal studies, possibly due to the challenges for tests comprising breath-by-breath assessments in swimming (Barbosa et al. 2015; Morais et al. 2018). Even though technique was the main contributor to improvements in 400-m time trial performance over the 48-weeks training season, rise in the anthropometrics influence was prominent. Likewise, SR was the best single contributor to improvements in the training season, followed by SI and height, suggesting that the improvements in performance of these age-group swimmers were also related to growth. In fact, even late to post pubertal age-group swimmers present a period of accelerated adaptation to training followed by improved swimming performance – i.e., a window of trainability where all systems still are very sensitive to training stimulus (McKay et al. 2016).

The diversification and increase of number of competitions led to the dissemination of the traditional three-peak preparation model – i.e., the typical macrocycle is replicated three times in a unique training season, usually with

progressive volume and T.U., like observed in Fig. 1 (Mujika et al. 1996; Issurin 2010). Thus, although each macrocycle has its own preparatory, specific and competitive periods, the following macrocycles are a step higher in intensity and volume, focusing on the main competition of the training season (Figs. 1 and 2). Despite that, age-group swimmers present a period of accelerated energetic and technique adaptation to training yet at the same time are at greater vulnerability to fatigue, illnesses and injuries (McKay et al. 2016). Progression of training through the macrocycles was  $\sim 10\% \cdot \text{week}^{-1}$ , which confirms the specific recommendations (increasing load in increments of 5-10% per week to prevent injuries made for athletes (Walsh et al. 2011; Hellard et al. 2015; Vanrenterghem et al. 2017). Additionally, the percentage of the individual maximal load observed within the macrocycles I, II and III ( $\sim 29\%$ ,  $29\%$  and  $14\%$  for taper;  $\sim 84\%$ ,  $\sim 82\%$  and  $\sim 65\%$  for short-term;  $\sim 91\%$ ,  $\sim 83\%$  and  $\sim 90\%$  for medium-term;  $\sim 77\%$ ,  $\sim 70\%$  and  $\sim 85\%$  for long-term) are comparable to improvements in middle distance performance by senior swimmers (Hellard et al. 2017).

The performance of competitive swimmers is closely matched even in swimming middle-distance events. Although progressions in swimming performance over a 12-month period leading up to the Olympic Games appear trivial, in closely matched races they can have a considerable effect on the result (Pyne et al. 2004). The 400-m freestyle is a relevant tool for performance analysis in competitive swimming. Even though many distances used in swimming events does not exceed 2 min, the aerobic power training zone is relevant and can be assessed with a single T400. In fact, the T400 is used to evaluate aerobic fitness and training intensities prescription (Lavoie and Montpetit 1986; Zacca et al. 2017). The T400 was sufficiently sensitive to identify the main changes during a traditional three-peak preparation program. However, it is important to recognize some limitations of the present study design. Although this study had the same design as our earlier one, the effects within a macrocycle as well as during within an entire season should be analyzed separately due the large volume of data. It was expected that swimmers would reach their best performances during the main competition of the macrocycle III, but this goal was achieved by  $\sim 70\%$  of the swimmers (17/24). In fact, although not statistically significant, mean change ( $\Delta$ ) between specific and competitive training periods was lower for increase

in  $\dot{E}$  than mean changes of rises in C (Table 1). However, since the last evaluation (E4) could only be performed after the main competition (Fig. 1), there may have been residual fatigue or possibly compromised motivation.

In conclusion, improvements in technique had the biggest influence on performance of T400 in age-group swimmers' performance, supported by improvements in energetics (fitness) and underlying growth and physical maturation. These outcomes support the primary role of technique development in age-group swimmers as consequence of an effective planning and coaching throughout the 48-weeks three-peak training season. Although swimming technique was the greater contributor for changes in performance of T400 over a traditional three-peak preparation program, it is closely connected with energetics. Therefore, a powerful and endurable metabolic base cannot be overlooked. Likewise, Swimming coaches and performance analysts should be aware of the growth effects, since even late to post pubertal age-group swimmers still are sensitive to training stimulus. Training periodization is a dynamic process, with a variable pattern of changes in key technical, energetic and anthropometric characteristics. Thus, swimmers should be evaluated regularly by coaches and sports scientists over the training season.



## Chapter 7 General Discussion

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The present thesis aimed to follow-up age-group competitive swimmers during an entire season, making an integrative assessment of biological and physical domains, checking whether a single T400 is sensitive enough to identify the improvement, maintenance or worsening of swimmers capacities, being a reliable tool for evaluation and prescription of swimming training. Early on we encountered the difficulty of defining a protocol, reliable and feasible enough that we could follow a team of swimmers. The best alternative available was the T400, but this had not yet been tested against a standard gold standard protocol (7 x 200-m incremental intermittent protocol; Fernandes et al. 2003, Pyne et al. 2001). Thus, we began with a methodological study (**Chapter 2**), validating this attractive protocol for age-group swimmers, which is characterized by strong ecological validity – i.e., reflecting real swimming conditions, unlike laboratory settings. We compared two methods, verifying whether the new one is worth employing. Given the strong relationship observed between T400 and  $\dot{V}O_{2max}$ , we considered the T400 valid. We are aware that the gold standard 7 x 200-m incremental intermittent protocol (Fernandes et al. 2003, Pyne et al. 2001) would give additional worthwhile information on training-induced adaptations over the T400, but this test would make our follow-up study unfeasible, since squads age-group swimming training and testing sessions are larger and sports science support is very difficult to come by (even more when adding breath-by-breath  $\dot{V}O_2$  assessment in swimming). Thus, we established through this study a significant departure from what had been published in the literature, defining the T400 as the protocol to be used during the follow-up, which is convenient, easy to conduct for assessing  $\dot{V}O_{2max}$  in age-group swimmers, and now, valid.

Armed with that valid protocol (**Chapter 2**), we had another methodological problem to solve before beginning the follow-up with age-group swimmers. Performance analysts spend several hours to give unbiased information for competitors and coaches, helping them to understand and improve performance. Nowadays, the use of technology and software by these professionals is decisive. Given that rapid feedback from test sets are necessary for coaches to better plan the training workouts, tools for editing, processing, filtering and modelling the  $\dot{V}O_2$  response should be available, effective and relatively straightforward.

Nevertheless, free and open-source software supported by these features is not yet available. This would make it unfeasible to perform a follow-up study with  $\dot{V}O_2$  kinetics analysis in swimming due to the considerable number of required analyses for each experiment. In situations like these, researchers and performance analysts frequently need to develop customised in-house tools, which require mastery of complex for mathematical modelling. Thus, we developed, described and evaluated a  $\dot{V}O_2$  fitting tool (VO<sub>2</sub>FITTING) for dynamically editing, processing, filtering and modelling  $\dot{V}O_2$  responses to exercise (**Chapter 3**). The VO<sub>2</sub>FITTING is valid, freely available and open source software with long-term utility. VO<sub>2</sub>FITTING was developed to help us in the follow-up with age-group swimmers and also the research and performance analysis community, allowing a straightforward analysis of  $\dot{V}O_2$  kinetics in exercise with a feasible graphical interface. Open-source software is a powerful tool modern coaches and performance analysts have at their disposal. As a valuable yet cost-effective, which is changing the landscape of tech development, this open-source software allows exercise physiologists to benefit from and build off the work of entire sport communities, taking advantage and exploring that tool instead of starting from scratch.

A critical issue for the follow-up was solved when we came across the result of comparing the mono- and bi-exponential models (**Chapter 3**). We performed one experiment using VO<sub>2</sub>FITTING with data from a T400. It is well reported that the workload demand during severe intensity exercise leads to a loss of muscle metabolic homeostasis that compromises the muscle power output, requiring additional motor unit recruitment and increased oxygen cost forming the  $\dot{V}O_{2sc}$  (Burnley & Jones 2018). However, although the bi-exponential model was the best fit for 75% of the current sample when comparing with the mono-exponential model, the sum of squares residuals when fitting this model was smaller for all swimmers (**Chapter 3**). As mentioned in **Chapter 3**, this contradiction may be explained by the inherent breath-by-breath noise observed in young swimmer's response profiles, probably masking changes in ventilatory variables (Fawkner & Armstrong 2004). However, even without significant differences observed between mono- and bi-exponential models for the remaining five swimmers, the mean  $A_{sc}$  (2.5 and 5.9 mL·kg<sup>-1</sup>·min<sup>-1</sup> for mono- and bi-exponential, respectively)

calculated as the difference between the  $\dot{V}O_2$  at the end and the amplitude of the primary phase was  $\geq 2.1 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$  (**Chapter 3**). Based on these results confronted with the literature, we defined the mono-exponential model for the longitudinal studies. (**Chapter 4, Chapter 5 and Chapter 6**).

By the **Chapter 4**, we started following an age-group swimming team during a competitive season, particularly in the off-season. In this study, we aimed to assess the performance, physiological and biomechanical effects of a typical off-season period in age-group swimmers, controlling growth and non-swimming specific physical activities performed during this period of swimming training cessation. We observed that detraining after four-weeks of pool-based training cessation can impair swimming performance at the start of the following training season in age-group swimmers, highlighting the importance of maintaining fitness levels during off-season. Besides, we observed a swimming performance reduction by 3.8% after four-weeks of training cessation in competitive 14-15 years old swimmers. Impaired performance was mainly associated with reductions in SR, increase in  $[\text{La}]_{\text{peak}}$  and non-swimming specific physical activities. Four-weeks was not long enough to detect a growth effect on performance, but impairment of T400 performance was attenuated by those swimmers who were more physically active during the off-season. These results reinforce the importance to provide instructions for age-group swimmers to be physically active when enjoying the off-season.

The aim of the **Chapter 5** was to quantify the changes in the energetics, technique and anthropometric profile while following age-group swimmers over the first macrocycle of the competitive season, comparing their variations and figuring out their relative contributions according to a traditional three-peak training program. The current study provided a biophysical overview of the key suppliers to performance during the first 16-weeks macrocycle from a competitive season (Issurin 2010; Turner 2011; Vorontsov 2011). We verified that T400 was a sensitive protocol, identifying changes in energetics, technique and anthropometric profile in age-group swimmers. Technique was the main contributor in the first macrocycle of traditional three-peak preparation program.

The marked influence observed in SR, SL and SI for changes in T400 were evident, perhaps, due to the close mathematical relationship between these

variables (Costill et al. 1985; Morais et al. 2014). Likewise, the lower energetic contribution may have been also influenced by the intra-/inter-subject variability and the degree of reliability in age-group testing protocols (Capelli 1999, Reis et al. 2012; Morais et al. 2014). Thus, a powerful and endurable energetic profile cannot be ignored since the progression of technique improvements is closely linked to energetic enhancements. Likewise, this study reinforces the importance of being alert to the age and maturity of swimmers particularly during periods of growth, since even late to post pubertal age-group swimmers are sensitive to training stimulus.

Finally, during **Chapter 6**, we compared changes in the energetics, technique and anthropometric profile while following age-group swimmers over a competitive season, comparing the fluctuations in contribution for these domains and figuring out their relative contributions according to a traditional three-peak preparation design (Issurin, 2010). The swimmers were evaluated before and after the macrocycle I, macrocycle II and macrocycle III, in which technique also played the main role during the competitive season, regardless of gradual increase in the influence of energetics and anthropometrics. As in **Chapter 5**, the results from the present study (**Chapter 6**) suggest that technique variables are more influential when introduced into regression analysis, which was more evident when using the delta values for each macrocycle during the follow-up, i.e., even with minor variations in performance over time, technique variables are still sensitive to explain swimming performance improvement. On the other hand, although slight changes in performance are also associated with changes in some energetic-related variables, these are not robust enough to show a consistent influence of energetics in swimming performance improvement (Capelli 1999, Reis et al. 2012; Morais et al. 2014)

The assessment of energetics, technique and anthropometrics factors associated with performance provide important insights for swimmers. Longitudinal studies are a small proportion of published articles in research community, which highlights the need for further studies to better understand factors influencing swimming performance (**Appendix I**). This lack in the peer reviewed literature gives value to the effort to carry out these longitudinal studies (**Chapter 4, 5 and 6**). It is important to highlight the difficulty of keeping a sample of participants with



this profile (competitive age-group swimmers) mobilized and motivated to perform so many moments of evaluation in a competitive season. Although this study had the same design as our earlier one, the effects within a macrocycle as well as during within an entire season should be analyzed separately due the large volume of data. Despite that, these studies provided valuable information for the progress of knowledge in aquatic sports.

Together, these three last longitudinal studies presented elucidate some concepts that until then had a very strong theoretical support and were rarely supported experimentally due to the great complexity to execute them. For instance, the  $\dot{V}O_2$  kinetics and the contribution of each parameter to performance had not been evaluated longitudinally in swimmers (Lätt et al., 2009; Armstrong & Barker 2009; Breese et al., 2010). In the same way,  $E_{tot}$  (in which Aer was estimated with breath-by-breath  $\dot{V}O_2$  data) and C were observed longitudinally, which gives a great contribution to the sports and scientific community. Until now, the few studies that evaluated the longitudinal behaviour of these variables in young swimmers were obtained with retro-extrapolation  $\dot{V}O_2$  data (Lätt et al. 2009).



## Chapter 8 Conclusions

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The findings attained in the collection of studies presented in this Thesis provide some relevant tools for sports/research community and highlights the importance of the biophysical approach to evaluate swimming performance through longitudinal designs. It can be concluded that:

- I. Incremental intermittent (7 x 200-m incremental intermittent protocol) and time trial (T400) protocols are broadly comparable in terms of physiological and biomechanical characteristics in competitive 14-15 years old swimmers;
- II. The T400 is a valid and easier option for aerobic power assessment in age-group swimmers, since it showed similar physiological and biomechanical responses to the 7<sup>th</sup> 200-m step ( $\dot{V}O_{2max}$ ). These outcomes confirm the viability of the T400 in monitoring the fitness, performance and technical characteristics of age-group swimmers;
- III. The use of the 7 x 200-m incremental intermittent protocol) and time trial (T400) protocols interchangeably is not recommended, since minor bias in  $v$  can occur when prescribing training sets;
- IV. The  $VO_2$ FITTING is valid, freely available and open source software with long-term utility;
- V. Despite the mandatory knowledge of respiratory physiology required for research and performance analysts when characterising  $\dot{V}O_2$  kinetics in exercise, some existing procedures for modelling are not easily applied, since they require mastery of complex software for mathematical modelling. Although some currently available commercial software provides the end-user straightforward options for  $\dot{V}O_2$  kinetics data analysis, freely available software supported by these features is not yet available. Thus, end-users usually need to develop customised in-house tools;
- VI.  $VO_2$ FITTING was developed to help the research and performance analysis community, allowing straightforward analysis of  $\dot{V}O_2$  kinetics in exercise with a feasible graphical interface;

- VII. The T400 was sensitive to identify the energetics, technique and anthropometrics changes and contributions during, off-season, first macrocycle of the training season and during a traditional three-peak preparation model in competitive 14-15 years old swimmers;
- VIII. Detraining after four-weeks of pool-based training cessation can impair swimming performance at the start of the following training season in competitive 14-15 years old swimmers, highlighting the importance of maintaining fitness levels during off-season;
- IX. Swimming performance at the 400-m front crawl was reduced by 3.8% after four-weeks of training cessation in competitive 14-15 years old swimmers. Impaired performance was mainly associated with reductions in SR, increase in  $[La^-]_{peak}$  and non-swimming specific physical activities;
- X. Four-weeks was not long enough to detect a growth effect on performance in competitive 14-15 years old swimmers. However, impairment of T400 performance was attenuated by those swimmers who were more physically active during the off-season;
- XI. Coaches should provide instructions for age-group swimmers to be physically active when enjoying the off-season;
- XII. Regarding the first macrocycle of traditional three-peak preparation program, technique played the main role during the first 16-week macrocycle in a competitive season, regardless of small fluctuations in the influence of energetics and anthropometrics.;
- XIII. During a traditional three-peak preparation model for competitive 14-15 years old swimmers, improvements in technique had also the biggest influence on T400 in age-group swimmers' performance, supported by improvements in energetics (fitness) and underlying growth and physical maturation. These outcomes support the primary role of technique development in age-group swimmers as consequence of an effective planning and coaching throughout the 48-weeks three-peak training season;
- XIV. The marked influence observed in technique variables for changes in T400 were evident, perhaps, due to the close mathematical relationship between these variables and performance or swimming speed. Likewise, the lower energetic contribution may have been also influenced by the

intra-/inter-subject variability and the degree of reliability in age-group testing protocols. Despite higher influence of technique, a powerful and enduring metabolic base cannot be overlooked, since technique is closely connected with energetics. Likewise, it is important to be aware of the growth effects, since late to post pubertal age-group swimmers still are sensitive to training stimulus;

- XV. Coaches and performance analysts should be aware that training periodization is a dynamic process, with a variable pattern of changes in key technical, energetic and anthropometric characteristics. Thus, swimmers should be evaluated regularly by coaches and sports scientists over the training season.

We strongly believe that the findings from these studies presented can contribute to a better understanding of the relationships between performance-related domains, highlighting the importance of longitudinal biophysical analysis for performance improvement.



## Chapter 9 Recommendations for future research

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Performance analysis of age-group swimmers during a training season, definitively, was not an easy task. From the choice of methodologies, testing and validation of protocols and resources for the follow-up of swimmers, several difficulties have arisen along the way. In this sense, I will list some recommendations for future studies:

- i. A familiarization of swimming with snorkels + noseclips, for several weeks prior to any experiment with  $\dot{V}O_2$  kinetics in swimming, is key point for a reliable and successful data collection. It should not be underestimated;
- ii. Researchers should be creative and give their best to keep age-group swimmers motivated in each evaluation, mainly after an important competitive event;
- iii. Future studies investigating the effects of gender and swimming technique/distance specialty on 7 x 200 m incremental intermittent protocol and T400 are recommended. Likewise, examining the small bias in  $v$ , SL and SI during time to exhaustion at  $\dot{V}O_{2max}$ , as well as studies comparing metabolic power and energy cost between both protocols, are welcome.
- iv. We wish to perform and also to invite the scientific community to conduct their experiments using  $VO_2FITTING$ . Likewise, we invite worldwide performance analysts to enjoy this new tool. Since  $VO_2FITTING$  is an open-source software (i.e. users can see how it works and add to it) with long-term utility, it can be continuously improved.
- v. Training periodization is a dynamic process, thus more longitudinal studies are strongly recommended to better understand the relationship between different areas.
- vi. We did not discard the possibility to test different statistical approaches with the same and/or other data, checking again and comparing the influence of energetics and technique. Despite that, it is important to keep in mind that training response is not a simple mathematical rationale.





## Chapter 10 References

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### Chapter 1

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## Appendix I

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### **Longitudinal Data over the International Symposium in Biomechanics and Medicine in Swimming: 1970 to 2014**

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## **Abstract**

Longitudinal studies in swimming are characterized by continuous or repeated data (quantitative, qualitative or both) collected over a period of at least two or more logically spaced time points, involving a combination of exposures and outcomes. Typically, longitudinal studies are stronger for examining cause-and-effect relationships than simple cross-sectional studies. However, they are logistically difficult, time-consuming to conduct and prone to swimmer drop-outs. Here we quantified the frequency of longitudinal studies, particularly in the biophysical domain, published in the proceedings books of the International Symposium in Biomechanics and Medicine in Swimming (BMS) over a 45-year period. A computer database search was conducted on all full articles published in the BMS conference proceedings (1970 – 2014) using a combination of relevant search terms. Longitudinal studies still are a small proportion of the total articles published in the BMS. Although interdisciplinary studies are more difficult to perform, they provide valuable information for the progress of knowledge in aquatic sports.

**Key words:** swimming, longitudinal, biophysical, biomechanics, physiology, psychology, pedagogy.



## **Introduction**

The Biomechanics and Medicine in Swimming (BMS) is a series of international symposia organized every four years. The BMS series started in 1970, in Brussels, by the hands of L. Lewillie and J.P. Clarys, with the first proceedings book published one year later (Vilas-Boas 2014). Since 1970, 12 scientific BMS books have been published (the 13th being the present volume), charting the progress of swimming knowledge. Although BMS papers do not necessarily form a fully indexed database of scientific literature, they are peer reviewed by impartial experts, thus providing relevant knowledge for the aquatic sport community.

Understanding more about a swimmer's potential requires organized, systematic and consistent training and evaluation providing to the coach useful scientific information on improvement, stagnation or deterioration in training and competitive performance. Since the goal of competitive swimmers is to complete the race distance as fast as possible, the technical, training and tactical factors that influence performance are attractive in swimming science. Testing swimmers during training allows coaches to follow their development, assess the effects of previous training, profile their main capabilities and predict performance.

Longitudinal studies are characterized by continuous or repeated data (quantitative, qualitative or both) collected over a period of at least two or more logically spaced time points, involving a combination of exposures, interventions and outcomes. Typically, these studies are stronger for examining cause-and-effect relationships than simple cross-sectional approaches. However, longitudinal studies are logistically difficult, time-consuming to conduct and prone to swimmer drop-outs.

Swimming performance is multi-factorial in nature in which biological and physical domains are involved (Figueiredo et al. 2013). Studies addressing both domains are designated biophysical approaches, allowing a deeper understanding of the swimming determinant variables and how they interplay to enhance performance (Pendergast et al. 2006). However, few studies have been conducted in this field, most likely due to the difficulty in conducting this type of research in the aquatic environment. The aim of this study was to quantify the frequency of longitudinal studies, particularly those conducted in the biophysical domain, published in the

proceedings books of the International Symposium in Biomechanics and Medicine in Swimming over a 45-year period.

## **Methods**

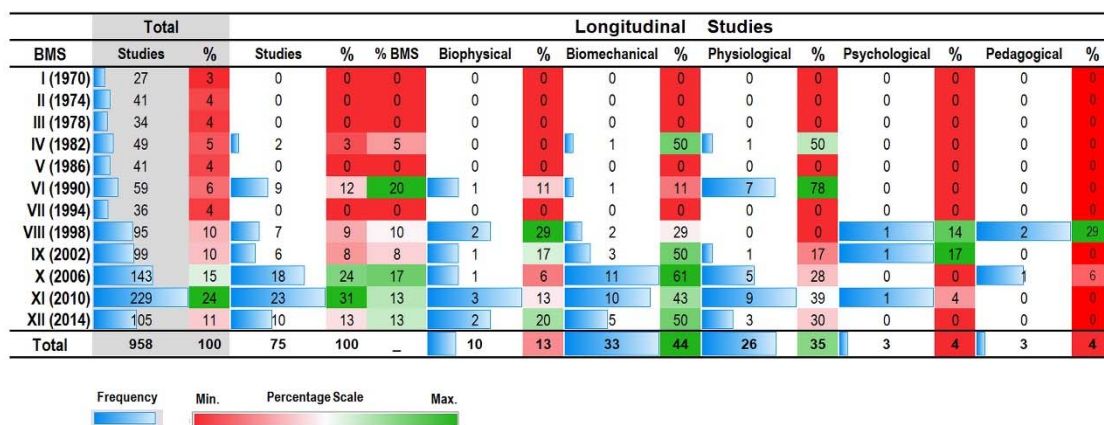
A three-part computer database search was conducted on all full articles published in the BMS conference proceedings (1970 – 2014) using a combination of relevant search terms. The first search targeted the longitudinal design using the search terms “longitudinal”, “cohort”, “prospective”, “follow-up”, “retrospective”, “prospective”, “training season”, “training period”, “mesocycle”, “macrocycle”, “weeks”, “months” and “Pre-Post”.

The second search evaluated the BMS book edition (year) and the last search quantified the frequencies of each longitudinal research domain, in which four longitudinal research domains were identified: (i) biomechanical (including hydrodynamics, kinematics, kinetics, stroke parameters analysis and coordination); physiological (including biochemistry, nutrition, ergogenic aids and supplements, and thermoregulation studies); (iii) biophysical (including efficiency and energy cost, as well as those that explicitly tried to relate biomechanical and physiological approaches); (iv) psychological and pedagogical scientific content (studies related to understanding human behavior in exercise and aquatic sports performance). Longitudinal approaches on pedagogical and educational water activities were also identified. Descriptive statistics were summarized with frequencies and percentages, and least-squares regression analysis was applied.

## **Results**

There was an exponential increase ( $r^2=0.77$ ) in the number of studies published in the BMS conference proceedings between 1970 and 2014. However, from 958 published articles, only 75 (8%) longitudinal studies were identified, in which 33 (44%) were biomechanical, 26 (35%) physiological, 10 (13%) biophysical, 3 (4%) psychological and 3 (4%) pedagogical approaches (Fig 1). In addition, a linear increase of the number of longitudinal studies in the BMS conference proceedings ( $r^2=0.60$ ) was evident, as well as higher frequency of longitudinal studies in the biophysical domain ( $r^2=0.65$ ).

**Fig 1.** Frequency and percentage scale of total and longitudinal studies in the proceedings books of the International Symposium in Biomechanics and Medicine in Swimming over a 35-year period.



## Discussion

This study confirmed the notion that longitudinal studies only form a small proportion of the total articles published at the BMS. The contribution of biomechanics over BMS editions was remarkable. Since 2006, the number of biomechanical longitudinal approaches showed an expressive increase, reinforcing the relative importance of this area of knowledge in swimming science. Although the inclusion of “biomechanics” on name of the series (“Biomechanics and Medicine in Swimming”) may have been influenced this distribution (Vilas-Boas 2014), the relevance of swimming technique and biomechanics as determinant factors for swimming performance cannot be overlooked. The importance of biomechanics in predicting swimming performance or speed may be relate to the close mathematical relationship between some related variables and performance or swimming speed (Costill et al. 1985). Despite that, evidence of lower energetic contribution to swimming performance may have been also influenced by the intra-/inter-subject variability and the degree of reliability in testing protocols (Reis et al. 2012; Morais et al. 2014). Thus, a progressive build-up aiming for a powerful and endurable metabolic base cannot be ignored since physiological factors are closely linked to biomechanics (Costa et al. 2006; Vanrenterghem et al. 2017).

Planning and evaluation swimming programs need to consider how physiology and biomechanics can be developed in both, isolation and combination. Although a better understanding of that relationship is relevant for aquatic community, there are few biophysical longitudinal studies available in the BMS series. In fact, biophysical longitudinal research is also scarce in scientific databases of peer-reviewed literature (e.g. PubMed and Scopus).

Psychology is a relevant area in aquatic sports, however it has been only sparingly explored in longitudinal designs in the BMS series. Despite that, the popularity of sports psychology has grown over the past two decades (Gee 2010), with a large number of publications supporting its applied use in sports performance development. In fact, sports psychology peer-reviewed related data on PubMed is showing an exponential increase since 2010. Being mentally prepared prior to a competition, as well as maintaining a particular mindset during competitions, is crucial (Gee 2010). Some aquatic coaches are still quite hesitant to seek out competent sport psychologists, despite the potential benefits, probably related to a lack of understanding about the process and the mechanisms in which these psychological skills affect aquatic performance (Gardner 2001).

Pedagogy is also a relevant domain in aquatic sports which not been extensively explored with longitudinal designs in the BMS series. Despite the relevance of energetics and biomechanics for aquatic performance, the techniques of learning are of essential importance (Light 2016). Learning to swim efficiently is not a basic task where the swimmers reproduce identical movements (Light and Wallian, 2008; Wizer et al. 2016). In addition, learning to swim should be a positive experience for both parents and young swimmers. However, this topic is underexplored in swimming research.

## **Conclusion**

Longitudinal studies form a small proportion of the total number of articles published at the BMS. Although interdisciplinary studies are more difficult to perform, they provide valuable information for enhancing knowledge in aquatic sports.

## **Acknowledgement**

The authors thank the support all those who were involved in this study. This work was funded by the by CAPES Foundation, Ministry of Education of Brazil, Brasília—DF, Brazil. The authors declare that they have no conflict of interest.