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Physiological and biomechanical characterization from low to severe swimming intensities. A study performed using a front crawl intermittent incremental protocol.

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"To accomplish great things, we must not only act, but also dream;
not only plan, but believe."
(Anatole France)

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To my grandfathers (Elísio de Jesus and Adolpho Goll — *in memoriam*).

To my grandmothers (Leonor Rodrigues de Jesus and Amanda Goll Klanschmidt — *in memoriam*).

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3. de Jesus, K., Sousa, A., de Jesus, K., Ribeiro, J., Machado, L., Rodríguez, F., Keskinen, K., Vilas-Boas, J.P., Fernandes, R.J. (2015). The effects of intensity on VO_2 kinetics during incremental free swimming. **Applied Physiology, Nutrition and Metabolism**, 40(9), 918-923. DOI: 10.1139/apnm-2015-0029.

4. de Jesus, K., de Jesus, K., Figueiredo, P., Vilas-Boas, J.P., Fernandes, R.J., Machado, L. (2015). Reconstruction accuracy assessment of surface and underwater 3D motion analysis. A new approach. Computational and Mathematical **Methods in Medicine**, Article ID 269264, 1-8. DOI: 101155/2015/269264.

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VI. Ribeiro, J., de Jesus, K., Figueiredo, P., Toussaint, T., Guidetti, L., Alves, F., Vilas-Boas, J.P., Fernandes, R.J. (2013). Biomechanical determinants of force production in front crawl swimming. **Journal of Sports and Medicine Physical Fitness**, 53, 30-37.

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Abstract

Our general purpose was to define the proper protocol step length and to detail its respective physiological and biomechanical characterization. Oxygen uptake kinetics (VO_2) and blood lactate concentrations [La-] have been assessed as well as kinematics and external upper limbs kinetics parameters. Comparisons among three variants of 7 times 200, 300 and 400 m have shown that 200 and 300 m accounted for a higher VO_2 plateau incidence and VO_2max values than 400 m step protocol using shorting time-average intervals (between 5 and 15 s). From a biomechanical perspective, comparisons among protocol variants did not reveal variations on general swimming and segmental kinematics, efficiency and inter-limb coordination parameters. Due to logistical reasons, the 200 m step length incremental test with short time-averaging intervals is recommended to accurately assess swimmers' VO_2 kinetics, [La-] and kinematics from low to severe intensities. VO_2 kinetics measured during 200 m step protocol remained stable within the low-moderate intensity, although fast VO_2 kinetics, great VO_2 gains in the primary component and a noticeable slow component ($\geq$ 255 ml. min^{-1}) were observed from heavy to severe intensities. For 200 m step protocol biomechanical characterization, a new three dimensional calibration frame has provided acceptable root mean square errors ($\leq$ 5 mm for surface and underwater views) to reconstruct two cycles of front crawl swimming technique. Through these two cycles assessed in two laps from each step intensity, swimmers depicted changes in general swimming and segmental kinematics and inter-limb coordination parameters, but, intracyclic velocity variations and propelling efficiency remained similar. This analysis is a new attempt to indicate novel insights in the selection of duration training sets at intensities below and above the anaerobic threshold.

Key words: Swimming, oxygen uptake kinetics, maximal oxygen uptake, time-averaging intervals, blood lactate concentrations, anaerobic threshold, incremental protocol.

Resumo

O objetivo geral desta Tese foi definir a distância mais adequada a ser utilizada em um protocolo incremental e intermitente e conduzir detalhadamente sua respectiva caracterização fisiológica e biomecânica. Foram analisados os parâmetros da cinética do consumo de oxigênio (VO_2), concentrações de lactato sanguíneo [La-], cinemática bidimensional e tridimensional e força dos membros superiores. As comparações entre as três variantes do protocolo incremental e intermitente (n ≤ 7 a 200, 300 e 400 m) evidenciaram que 200 e 300 m representaram maior incidência do platô do VO_2 à intensidade de $VO_{2máx}$, bem como maiores valores de $VO_{2máx}$ em relação ao protocolo de 400 m usando baixas frequências de amostragem (entre 5 e 15 s). Numa perspectiva biomecânica, as comparações entre as variantes de um protocol incremental e intermitente não revelaram alterações nos parâmetros da cinemática geral e segmentar do nado, eficiência e coordenação. Por razões logísticas, o protocolo com patamares de 200 m, usando baixas frequências de amostragem, foi recomendado para avaliar a cinética do VO_2, concentrações de lactato sanguíneo e cinemática desde intensidades de nado baixas à severas. Ao longo do protocolo incremental e intermitente de 200 m, a cinética do VO_2 mantevê-se estável durante à intensidade moderada, embora nas intensidades elevada e severa, a cinética do VO_2 foi mais rápida e evidenciou ganhos na componente primária do VO_2 e um notável aparecimento da componente lenta do VO_2 (≥ 255 ml. min^{-1}). No que concerne a caracterização biomecânica do protocolo incremental de 200 m, o novo volume de calibração tridimensional forneceu valores de erros médios aceitáveis (≤ 5 mm para as imagens de superfície e subaquáticas) para a reconstrução de ciclos de nado da técnica de crawl. Através destes dois ciclos de nado analisados em dois parciais de cada patamar de intensidade dos 200 m, foi observado que os nadadores alteraram a cinemática geral e segmentar e a coordenação do nado, embora, conseguiram manter as variações intracícílicas da velocidade e a eficiência propulsiva num padrão estável. Esta análise é a primeira tentativa objetiva de novas percepções na seleção do tempo de duração das séries de treino à intensidades abaixo e acima do limiar anaeróbio em natação.

Palavras chave: Natação Pura Desportiva, cinética do consumo de oxigênio, consumo máximo de oxigênio, frequências de amostragem, concentrações sanguineas de lactato, limiar anaeróbio, protocolo intermitente incremental.

Résumé

Le but de cette thèse fut donc de définir la longueur la plus appropriée des étapes du protocole incrémental intermittent et de mener en détail sa respective caractérisation physiologique et biomécanique. Pour atteindre cet objectif les cinétique de la consommation d' oxygène (VO_2) ainsi que la concentrations des lactates, deux et trois cinématiques dimensionnelles et la cinétique extérieure des membres supérieurs. Les comparaisons entre trois variantes de ce protocole (n ≤ 7 à 200, 300 et 400 m) ont montré que les 200 et les 300 m représentaient plus l'incidence du plateau de VO_2 aussi que les valeurs de VO_2max du protocole aux 400 m à l'aide des intervalles de temps de courte duration (entre 5 et 15 s). Du point de vue biomécanique les comparaisons entre ces variantes du protocole ont pas révélé des variations sur la natation en général et sur la cinématique segmentaire, sur l'efficacité et sur les paramètres de coordination inter-membres. Pour des raisons logistiques, l'épreuve de 200 m a été recommandée avec des intervalles courts pour évaluer avec précision le lactate du sang des nageurs, la cinétique et la cinématique du VO_2 de faible à intensité sévère. La cinétique du VO_2 mesurée pendant les 200 m du protocole est restée stable au sein de l'intensité faible à modérée, malgré qu'une cinétique de VO_2 plus rapide, de plus grands gains de VO_2 dans le composant principal et un composant lent évident (≥ 255 ml. min^{-1}) ont été observés à partir de l'intensité lourd à l'intensité sévère. Pour la caractérisation biomécanique des 200 m du protocole, le nouveau cadre de calibrage á trois dimensions a fourni des erreurs acceptables en regardant la moyenne de la racine carrée (≤ 5 mm pour la surface et sous surface) pour reconstruire deux cycles de technique de nage crawl. Au milieu de l´évaluation de ces deux cycles dans deux tours de chaque intensité de l'étape, les nageurs ont montré la cinématique segmentaire et générale de la natation et les changements de coordination inter-membres. Toutefois, la fluctuation intracyclique de la vitesse et l'efficacité de propulsion ont restée semblables. Cette analyse est la première tentative objective d'indiquer des nouvelles perspectives dans la sélection des sets d'entrainement de duration aux intensités au-dessous et par-dessus du seuil anaérobique.

Mots clés: Natation, cinétique de la consommation d’oxygène, cinétique de la consommation d’ oxygène, moyenne d’ intervalle de temps, les concentrations des lactates dans de sang, seuil anaérobique, protocolo incrémental.

List of Abbreviations

Anova	Analysis of variance
APAS	Ariel Performance Analysis System
ATP	Adenosine Triphosphate
AnT	Anaerobic threshold
A_1	Amplitude of the VO_2 on-kinetics fast component
A_2	Amplitude of the VO_2 on-kinetics slow component
A_{200}	Amplitude of the VO_2 during the 200 m at intensity corresponding to maximum velocity
A_{Ian}	Amplitude of the VO_2 during the 200 m at intensity corresponding to to the individual anerobic threshold
a	Intercept
b	Slope
bpm	Beats per minute
b x b	Breath by breath
BD	Horizontal hands backward displacement
CO_2	Carbon dioxide
CI	Confidence interval
CV	Coefficient of variation
d	Cohen effect size for *t* – statistic
df	Degrees of freedon
$IVVx_{CG}$	Horizontal intracyclic velocity variations of the centre of mass
$IVVy_{CG}$	Vertical intracyclic velocity variations of the centre of mass
DLT	Direct linear transformation algorithm
F	F - Statistics
h	Homography
H	Homography matrix
HR	Heart rate
Hz	Hertz
IdC	Index of coordination
IQR	Interquartile range
IVV	Intracyclic velocity variations
$[La^-]$	Blood lactate concentrations
Ian_{ind}	Intensity corresponding to the individual anerobic threshold
LEA	Left elbow ngle at the pull and push phases
LT	Lactate threshold

LHa	Left hip vertical amplitude
LFa	Left foot amplitude
LFv	Vertical left foot speed during upbeats and downbeats
MAD system	Measure active drag force
n	Number of subjects
O_2	Oxygen
P	Probability
Q	Cardiac output
r	Correlation coefficient
R	Respiratory exchange ratio
REA	Right elbow angle at the pull and push phases
RMS	Root mean square
r^2	Person's correlation determination
RHa	Right hip vertical amplitude
RFa	Right foot amplitude
RFv	Vertical right foot speed during upbeats and downbeats
RPE	Perceived exertion
SD	Standard deviation
SF	Stroke frequency
SL	Stroke length
SPSS	Statistical package for social sciences
t	*t* statistic
TD	Time delay
TD_{200}	Time delay of the VO_2 during the 200 m at intensity corresponding to maximal velocity
TD_{Ian}	Time delay of the VO_2 during the 200 m at intensity corresponding to the individual anerobic threshold
Tlimit at vVO_2max	Time to exhaustion at velocity corresponding to VO_2max
TI	Trunk obliquity
t	Time constant

t_1	Time constant of the VO_2 on-kinetics fast component
t_2	Time constant of the VO_2 on-kinetics slow component
t_{200}	Time constant of the VO_2 during the 200 m at intensity corresponding to the maximum velocity
t_{lan}	Time contant of the VO_2 during the 200 m at intensity corresponding to the individual anerobic threshold
v	Velocity, speed
VO_2	Oxygen uptake
VO_2b	Baseline oxygen uptake
VCO_2	Volume of carbon dioxide expired
VO_2max	Maximal oxygen uptake
VO_2peak	Peak oxygen uptake
vVO_2max	Minimum velocity that elicits VO_2max
VO_2SC	VO_2 slow component
v_{rhand}	Horizontal right hand speed
v_{lhand}	Horizontal left hand speed
w	Kendall's coefficient of condordance
x	Horizontal axis
y	Vertical axis
z	Lateral axis
2D	Two dimensional
3D	Three dimensional
nf	Froude efficiency
np	Propelling efficiency
η^2	Partial eta-squared
u and v	A group of 2D points for posterior homography analysis
Wd	Hydrodinamic resistance

Chapter 1 General Introduction

After the prohibition of the controversial swimsuits in March 2009 (that helped swimmers achieving more than 130 world records in less than two years), researchers and coaches were challenged in surpass the swimsuit era in the coming years. One of the main goals was the enhancement of swimmers' evaluation and training control, considered as fundamental tools to increase the efficiency of the training process and also to predict performance (Allen et al., 2014; Olbrecht, 2000; Pyne et al., 2000). This should be done by implementing a sets of tasks that allow the assessment of the results and adequacy of training programs, as well as the level of development of the determinant performance factors (Fernandes et al., 2009).

Antropometrics, hydrodynamics, psychology, pedagogy, medicine and traumatology are some of the areas used to understand swimming performance (Anderson et al., 2008; Barbosa et al., 2014; Lät et al., 2010; Papadopoulus et al., 2014). Even so, it is consensual that physiological and biomechanical factors are the most determinant to enhance performance and achieve high-standard levels in competitive swimming (Allen et al., 2014; Psycharakis et al., 2008; Toussaint & Beek, 1992). The physiological factors refer to the energy supply systems, from which the aerobic capacity and aerobic power pathways seem to present great relevance in swimming (Billat, 2001; Gastin, 2001; Rodríguez & Mader, 2010) and the biomechanical factors are greatly focused on motion analysis, in which kinematic assessment is considered crucial for swimming technique monitoring (Keskinen & Komi, 1993; Dadashi et al., 2012; Psycharakis et al., 2010). The present Thesis focuses on the assessment and characterization of the swimmers' physiological and biomechanical profile using a low to severe incremental swimming protocol.

It is well accepted that the aerobic energy system is one of the most important physiological mechanismos in the main competitive swimming events (Capelli et al., 1998; Medbo et al., 1988; Olbrecht, 2000; Rodríguez & Mader, 2010; Troup, 1984), especially after the recognition of a shift of the bioenergetics supply partition to a more aerobic zone for any particular duration of maximal competitive event, with exception for the 50 m distance (Gastin, 2001; Rodríguez & Mader, 2010; Troup, 1984). Along with the anaerobic threshold (AnT), the maximal oxygen uptake (VO_2max) and the minimum velocity that elicits VO_2max (vVO_2max), seem to be some the most important parameters for swimmer's aerobic potential evaluation (Pelayo et al., 2007; Reis et al., 2012; Rodríguez et al., 2015). According to Fernandes et al. (2003), VO_2max is widely assumed as a standard of maximal aerobic power and is associated with an exercise intensity related to one of the primary areas of interest in training and performance diagnostic in swimming. Other parameters, such as the time that the swimmer is able to sustain on vVO_2max (Time Limit at vVO_2max) and swimming economy (the inverse of the energy cost of locomotion) should also be considered as very important parameters to characterize swimmer's performance capacity (Chatard et al., 1990; Costill et al., 1985; Kjendlie et al., 2004; Smith et al., 2002).

The assessment of VO_2max, vVO_2max, Time Limit at vVO_2max and swimming economy require specific oximetry procedures and protocols (Billat et al., 1996; Demarie et al., 2001; Fernandes & Vilas Boas, 2012; Rodríguez et al., 2015). Normally, the first two parameters are evaluated using incremental protocols without resting periods between steps (Capelli et al., 1998; Pessoa Filho et al., 2012; Unnithan et al., 2009). However, swimming economy assessment requires both aerobic and anaerobic energy expenditure evaluations (Chatard et al., 1990; Vilas-Boas & Santos, 1994; Zamparo et al., 2011) at incremental swimming speeds to allow the computation of an economy curve. To do so, it is necessary to collect not only respiratory parameters, but also blood parameters (e.g. lactate concentrations, $[La^-]$), which requires the interruption of the protocol just after each step (Fernandes et al., 2009; Pyne et al., 2001; Toubekis et al., 2006). Thus, swimming researchers proposed intermittent incremental protocols with progressive sets of 200 m to assess VO_2max, AnT and swimming economy (Fernandes et al., 2006; Libicz et al., 2005; Pyne et al., 2001; Reis et al., 2012). However, physiologists claim that to accurate determine the $[La^-]$ and VO_2, steps of incremental protocols should be 4 min or more, once this is the minimum time required to occur a physiological stabilization (Bentley et al., 2007; Hill et al., 2003; Kuipers et al., 2003; Midgley et al., 2007b).

In individual cyclic sports, intermittent incremental protocols with different step durations were compared (such as running and cycling), being observed that those with shorter durations (between 2 and 3min) provide accurate [La^-] and VO_2 measurements (Bentley & McNaughton, 2003; Hill et al., 2003; Kuipers et al., 2003). Specifically in swimming, the gold stardand protocol for AnT assessment (the Maximal Lactate Steday State protocol – Max Lass) was compared with intermittent incremental protocol variants (with differents lengths: n x 200, 300 and 400 m), revealing that short and medium step durations (i.e. those with 200 and 300 m steps) were more proper to evaluate the swimmers' AnT (Fernandes et al., 2011). These findings allow to speculate that, as observed for [La^-] values, the protocol with shorter step lenghts would display the same behaviour for VO_2max values than the other ones, being an appropriated tool to assess swimmers' aerobic potential. This problematic justifies the development of the current Thesis.

Knowing that the best protocol step length is still a controversial issue, as it should comply with physiological parameters stabilization and coaches training schedule, we firstly developed a large spectrum of studies comparing different intermittent incremental protocol variants for VO_2max assessment from both (although not combined) physiological and biomechanical points of view (**Chapter 2, Appendix I** and **Appendix II**). Secondly, after defining what is the proper step length to use for swimmers evaluation and training control, we have conducted physiological and biomechanical related studies using the most proper: the 200 m (**Chapter 3** to **6** and **Appendix III** to **VI**). Thirdly, we elaborated a general discussion upon the results obtained from our experimental studies supported by the specialized literature (**Chapter 7**). Finally, the main conclusions, suggestions for future research and references used along the Thesis were presented in **Chapters 8**, **9** and **10**, respectively. A more detailed description of the experimental studies will now be made.

To obtain reliable and accurate VO_2max values during intermittent incremental protocols, appropriate methodologies should be adopted, meeting an adequate application of the step durations and a standardized criteria for VO_2max attainment (Fernandes & Vilas-Boas, 2012; Midgley et al., 2008; Smith et al., 2002). Beyond the fact that protocol step lengths influence VO_2max values, considerable inter-breath fluctuations provided from breath-by-breath technology in VO_2 assessment could also affect the VO_2max achievement (Hill et al. 2003; Midgley et al., 2007a; Midgley et al., 2008). Thus, the selection of an optimal sampling interval is fundamental for research findings validation, as well as to a correct training diagnosis and posterior series intensity prescription (Astorino, 2009; Myers et al., 1990; Özyener et al., 2001). To guide our subsequent work, we aimed to investigate the effects of different time-averaging intervals (i.e. breath-by-breath, 5, 10, 15, 20 and 30 s) on VO_2max values obtained in three protocol step lengths (with 200, 300 and 400 m) variants (**Appendix I**). In this pilot study, we aimed to establish a standard VO_2max time-averaging method, as well as to identify the proper step length to be used in the intermittent incremental protocol for a better VO_2 plateau incidence identification. It was hypothesized that the VO_2max would be greater when using short sampling intervals, particularly those ≤ 15 s, and that the 400 m step length will imply a higher VO_2 plateau incidence at VO_2max.

Besides the physiological variables, relevant biomechanical and motor control parameters should also be monitored during intermittent incremental protocols, providing coaches with detailed technical behaviour arising from respective environmental constraints (cf. Barbosa et al., 2008; Figueiredo et al., 2013; Komar et al., 2012; Psycharakis et al., 2008; Seifert et al., 2014): (i) general swimming kinematics (e.g. stroke frequency, stroke length and mean swim speed), (ii) segmental and anatomical kinematics (e.g. hands and feet speed), (iii) intracyclic velocity variations, (iv) efficiency (e.g. propelling efficiency) and (iv) inter-limb coordination (e.g. index of coordination). In fact, to select the proper step length for the intermittent incremental protocol, it is necessary that it would comply with accurate and reliable physiological assessment without meaningly affect energetics, kinematics and inter-limb coordination. Thus, it would be also interesting to verify if the intermittent incremental protocol variants studied would affect swimmers' technique.

Following this reasoning, it was aimed to conduct two kinematical studies comparing front crawl intermittent incremental protocol variants with 200, 300 and 400 m step lengths (**Chapter 2** and **Appendix II)**. In the former study (finalist of the Archimedes Award in the XII International Symposium on Biomechanics and Medicine in Swimming), it was proposed to assess efficiency and arm coordination using two front crawl cycles from the penultimate lap of each of the above referred variants of the incremental protocol. As more than one swimming cycle is recommended to accurately characterize swimmer's technique during a specific event lap (Seifert et al., 2010) and similar physiological profile among step lengths could be condicioned by similar technical responses variations, it was hypothesized that steps with differents lengths (from 200 to 400 m) would not affect selected kinematical parameters. In addition, to complement **Chapter 2** findings, it was proposed to observe if swimmers would change anatomical and segmental kinematics across step of 200, 300 and 400 m durations on an incremental protocol (**Appendix II**). As seen before that efficiency and inter-limb coordination would present similar profile among step lengths, it would not be expected relevant changes in anatomical and segmental kinematics.

Based on the previous findings, it was appropriated to conduct a depper characterization of the n x 200 m front carwl incremental protocol. VO_2max is well accepted as relevant paremeter for successful middle distance events, but VO_2 uptake is also recommended to be used to better define the bioenergetical training areas (Rodríguez & Mader, 2010). In fact, to provide reliable and accurate VO_2 values across low to severe intensities during an incremental protocol, researchers should conduct an appropriate VO_2 data treatment for subsequent training series prescription (Astorino 2009, Midgley et al., 2008; Myers et al., 1990). Following this idea, it was aimed to conduct two physiological studies (**Chapter 3** and **Appendix III**) focusing on the most accurate time-averaging intervals to be used for VO_2 assessment during the n x 200 m incremental protocol. So, in light of the scarcity of studies concerning suitable VO_2 data treatment methods in swimming, it was proposed to compare the most often used VO_2 time-averaging intervals (i.e. breath-by-breath and 5, 10, 15, 20 and 30 s), from low to severe intensities using a robust sample size of well-trained swimmers. Based on the literature (Özyener et al. 2001; Midgley et al., 2007a; Myers et al., 1990; Hill et al., 2003), it was hypothesized that the VO_2 values would be similar for all time averages studied when swimming at low-moderate and heavy intensities, but VO_2 values would be higher when using shorter time averaging intervals (≤ 15 s) at severe intensity . Complementarily, as VO_2peak (defined as the highest VO_2 value obtained during a specific effort; Day et al., 2003) is also relevant to characterize swimmers' aerobic potential (Rodríguez et al., 2003; Sousa et al., 2014), it was tested the time-averaging intervals for accuracy in its respective assessment (**Appendix III**).

After establishing the best time-averaging intervals to be used in VO_2 assessment, it was our aim to check the VO_2 magnitude and adjustment from low to severe intensity (**Chapter 4** and **Appendixes IV** and **V**). Firstly, it was proposed to conduct a pilot study that analyse and compare the VO_2 kinetics at AnT and VO_2max intensities (**Appendix IV**), both used by coaches during aerobic capacity and power development (Olbrecht, 2000; Reis et al., 2013). Comparisons of the VO2 kinetics behaviour between those two exercise intensities were conducted before in treadmill and cycle ergometer incremental protocols, being noted a faster VO_2 kinetics and a VO_2SC appearance at VO_2max intensity (Carter et al., 2000; Koppo et al., 2004; Özyener et al. 2001). In the light of those findings, it was hypothesized that similar results for VO_2 kinetics and VO_2SC would be observed at the referred intensities in swimming. Following this pilot study, it was proposed to extend previous comparisons to a wide range of common used training intensities (**Chapter 4**). Therefore, as swimming is also a cyclic modality, it would be expected a similar profile to those obtained during running and cycling protocols, which revealed a stable VO_2 kinetics pattern within low-moderate intensity (i.e. up to AnT) and a faster VO_2 kinetics profile at heavy and severe intensities (i.e. above AnT and around VO_2max, respectively) (Carter et al., 2000; Koppo et al., 2004). As the n x 200 m incremental protocol variant might be considered less time consuming for daily based training use, but the n x 300 m variant is still choosen as an alternative protocol (e.g. Komar et al., 2012), we considered relevant to compare the VO_2 kinetics during n x 200 and 300 m incremental protocol variants in the most specific swimming competition i.e. above AnT (**Appendix V**).

After determining the most appropriated intermittent incremental protocol variant for daily training use and conduct its respective physiological characterization, we considered also pertinent to deeply characterize its eventual 3D kinematical changes between steps and within laps. To achieve this goal, we redesigned previous used 3D calibration frame (e.g. Psycharakis et al., 2005), allowing recording of suitable swimming cycles number for proper swimmers' technique feedback (**Chapter 5**). It was hypothesized that larger calibration volumes could be implemented in swimming technical analysis if researchers controlling the main 3D reconstruction criteria (i.e. control and validations points number and location, cameras positioning and image distortion; Kwon & Casebolt, 2006). In addition, it would be pertinent to know how powerful video image correction methods could improve 3D swimming image reconstruction. For this purpose, we used the homography technique that has been often used in 3D image retification studies and considered as a key step to obtain faster and less erroneous 3D images reconstruction (e.g. Nejadasl & Lindenbergh, 2014). Therefore, it was hypothesized that considering 3D reconstruction criteria with homography implementation in swimming kinematics would improve double media movement analysis.

Gathering proper 3D kinematic methodology with our know-how in swimming technique analysis (e.g. Figueiredo et al., 2012), it would be timely to undertake a detailed description about the environmental and task constraints (i.e. between increments and within increments, respectively) imposed by n x 200 intermittent incremental protocol variant (**Chapter 6**). Kinematic studies conducted during intermittent incremental protocol considering differences between steps and laps have adopted a two-dimensional (2D) approach (Komar et al., 2012), which is normally selected due to the quickness in data collection and analysis for coaches' feedback (Yoshioka et al., 2010). As observed by Komar et al. (2012), swimmers changed general and segmental swimming kinematics, efficiency and inter-limb coordination to achieve respective protocol goals. However, as asymmetry is common noticed in bilateral skills performance (such as in swimming; Psycharakis et al., 2010), whenever possible, coaches and researchers should plan a 3D protocol to characterize efforts generated from low to severe intensities, complementing 2D findings. Based on previous kinematical studies considering front crawl swimming technique in a wide range of intensities (Komar et al., 2012) or at maximal effort (e.g. Figueiredo et al., 2012), it could be hyphotesized that when swimming speed increases, changes in kinematic and inter-limb coordination parameters would be noticed between and within 200 m increments.

Besides a detailed 3D kinematic analysis on 7 x 200 m incremental protocol variant (**Chapter 6**), the direct measurement of the propulsive forces while swimming front crawl in different speed increments required by the respective protocol is also an important parameter for swimmers' technical evaluation (Toussaint et al., 2004). According to Toussaint & Hollander (1994), during incremental swimming considerable energy expenditure is used to overcome water resistance and, changes in general swimming kinematics, efficiency and arm coordination are expectable. Thus, it would be important to note how upper limbs force could affect general swimming kinematics (i.e. speed, stroke length and stroke frequency), efficiency (i.e. intracyclic velocity variations), and arm coordination (i.e. index of stroke coordination) during a wide range of intensities (**Appendix VI**). It was suggested that, from low to severe intensities, high stroke frequency, optimal coordination and low intracyclic velocity variations seem to be required to produce high force values in front crawl swimming.

Chapter 2

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

***This study was finalist for the Archimedes Award in the XII International Symposium on Biomechanics and Medicine in Swimming. Canberra, Australia. May, 2014.**

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Abstract

This study aimed to compare incremental and intermittent protocols with different step lengths to observe eventual changes in technique related parameters. Eleven national level swimmers (20.4±2.5 yrs, 1.80±0.06 m, and 74.1±4.12 kg) performed three variants of a front crawl incremental and intermittent protocol (7x200, 7x300 and 7x400 m) until exhaustion, with increments of 0.05 $m.s^{-1}$ and 30 s rest intervals between step and 48h between each protocol variant. Swimmers were videotaped in the sagittal plane at the penultimate lap of each step of each variant, using a dual media set-up. APASystem was used to obtain the swim efficiency and arm coordination parameters: (i) intracycle speed variation of the horizontal swimmer's hip displacement (IVV); (ii) difference between the maximal and minimal horizontal hip velocity within the stroke cycle (dv); (iii) propelling efficiency (np) and index of coordination (IdC). Comparison among the three variants of the incremental protocol did not show differences for swim efficiency and arm coordination. The results for IVV, dv, np, IdC for 7x200, 7x300 and 7x400 m were, respectively: (i) 0.16 to 0.18, 0.21 to 0.23, 0.20 to 0.21; (ii) 1.08 to 1.12, 1.05 to 1.26, 0.80 to 0.95; (iii) 1.47 to 1.78, 1.52 to 1.89, 1.54 to 1.80; (iv) -7.6 to -1.89, -8.41 to -0.18, and -7.37 to -0.14. All the comparisons for a Mean Rank > 1.50 and a *P* value > 0.05. Since there were no differences between the three protocol variants, the one with shortest step length (i.e.200 m) should be adopted due to practical and pragmatic reasons.

Key words: kinematics, efficiency, index of coordination, front crawl.

Introduction

Traditionally, incremental protocols have been implemented without stopping the exercise, i.e., by continuously increasing the exercise intensity between steps. However, in swimming, the implementation of short resting intervals between steps is required, so swimmers can receive proper feedbacks and researchers can collect capillary blood samples (to assess lactate kinetics and energy cost of locomotion and, control swimming intensity through scores of perceived exhaustion (Fernandes et al., 2005). Recently, Fernandes et al. (2011) compared the effect of different variants (steps of 200 vs 300 vs 400 m) of an incremental protocol on physiological parameters and observed that the velocity and the heart rate corresponding to individual anaerobic threshold, the blood lactate concentrations and heart rate maximal values were similar. The only exception was the higher blood lactate values at individual anaerobic threshold in the 200 and 300 m compared to 400 m variant. Then in a study about maximal oxygen uptake characterization, Fernandes et al. (2012) reported that the 200 and 300 m variants accounted for higher percentage of oxygen consumption plateau incidence and higher maximal oxygen consumption values compared to the 400 m step protocol. Over all, these studies concluded that the 200 m incremental protocol is the most suitable to be used, as it decreases the logistic time need to individually assess swimmers, without a significant impact on validity and accuracy of the physiologic data collected.

Despite the previous statements, the n x 200 (300 or 400 m) intermittent incremental protocol has also been analysed to assess the swimmers biomechanical and motor control characteristics. In fact, several biomechanical variables are particularly related to swimming efficiency (e.g. propulsive efficiency and intracycle speed variation) (Barbosa et al., 2008; Komar et al., 2012) and inter limb-coordination (e.g. index of coordination) (Komar et al., 2012; Figueiredo et al., 2013). However, to use a protocol variant with shorter step length it would not affect significantly energetics, kinematics and inter-limb coordination (Fernandes et al. 2011), but until now no research comparing swimmer's efficiency biomechanics and coordination during an intermittent incremental protocol with different step lengths was done. So, the purpose of this study was to compare three variants of an intermittent incremental protocol to observe eventual changes in technique related parameters. It was hypothesized that there are no significant differences in swim efficiency and inter-limb coordination variables induced by shorter step lengths, and for pragmatic reasons, a shortest step distance should be selected.

Material and Methods

Participants

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

Procedures

All tests sessions took place in a 25 m indoor swimming pool, 1.90 m deep, with water temperature at 27.5ºC. A standardized warm-up, consisting of 1000 m of swimming at low-to-moderate intensity, was conducted before each variant of the protocol. Using in water starts and flip turns, each participant performed, in randomized order, three variants of the front crawl intermittent incremental protocol until exhaustion (7x200, 7x300 and 7x400 m). Each variant had increments of 0.05 $m{\cdot}s^{-1}$ between steps and 30 s intervals. The predefined velocity of the last step was common to all variants, being established according to each swimmer personal best at 400 m front crawl swimming at that time of the experiments. Then, 0.05 $m.s^{-1}$ was successively subtracted, allowing the determination of the mean target velocity for each step of the incremental protocol (Fernandes et al., 2011). The swimming pace of each step was common to the three protocol’s variants and controlled through a visual pacer with flashing lights on the bottom of the pool (TAR. 1.1, GBK-Electronics, Aveiro, Portugal). In addition, elapsed time was measured with a stopwatch (Seiko chronometer) to assess the exact swimmer's speed. A 48 h resting period was respected between each protocol variant and swimmers were asked to abstain from strenuous exercise during the testing period. All the subjects were able to perform 7x200 and 7x300 m, but only eight swimmers completed totally the 7th step of the 7x400 m protocol variant at the pre-defined velocity.

Data Collection

Swimmers were videotaped in the sagittal plane for 2D kinematical analysis using a dual-media set-up, with both cameras (Sony, DCR-HC 42E, Nagoya, Japan) operating at a sampling frequency of 50 Hz, with 1/250 of digital shutter speed, fixed on a home-made designed support for video image recording (Figueiredo et al., 2013; Vilas-Boas, 1996) (Figure 1).

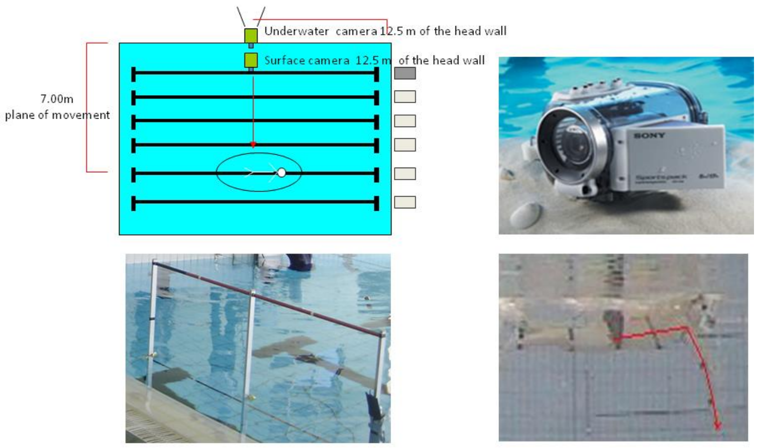

Figure 1. Schematic diagram of the camera set

This support was placed at the lateral pool wall, 12.5 m from the head wall, with cameras positioned 30 cm above and below the water surface and 7 m from the plane of movement. The underwater camera was kept in a waterproof housing (Sony SPK-HCB box) exactly below the surface camera. The swimmers were monitored when passing through a specific pre-calibrated space using a 2D calibration frame (6.3 m^2) and images from both cameras were recorded independently. Each camera recorded a space of 4.5 m long for the XX-axis, and participants wear specific anatomical markers on upper limbs and trunk. Synchronization of the images was obtained through a pair of LEDs, fixed to the calibration volume and visible in the field of view of each camera.

Video images were manually digitized frame-by-frame (f=50 Hz) using a specific processing software (Ariel Performance Analysis System, Ariel Dynamics, USA) to obtain paired raw coordinates (x, y), and consecutive differentiation to obtain velocity. The analysis period comprised one complete upper limbs cycle in the penultimate lap of each step of each protocol variant (i.e. 175, 275 and 375 m). To eliminate the possible effects of breathing on the studied variables, swimmers were instructed to perform non-breathing cycles when passing in the calibrated space. It was used the anthropometric model from Zatsiorsky & Seluyanov (1983) adapted by de Leva (1996), including nine anatomical landmarks from the upper body, the acromion, lateral humeral epicondyle, ulnar styloid process, third distal phalanx and prominence of great femoral trochanter. Six calibration points and DLT algorithm (Abdel-Aziz & Karara, 1971) were used for 2D reconstruction. The selection of a 5 Hz cut-off value for data filtering (with a low pass digital filter) had to be done according to residual analysis (residual errors vs cut-off frequency). Root Mean Square (RMS) reconstructions errors of six validations points on the calibration frame, which did not serve as control points, for the horizontal and vertical axes were, respectively: (i) 1.92 mm and 1.78 mm, representing 0.33 and 0.40% of calibrated space of above water; and (ii) 1.84 mm and 1.71 mm, representing, 0.38 and 0.43% of the calibrated space for underwater.

For the efficiency estimation, were selected the following parameters: (i) intracycle speed variation of the swimmer's hip horizontal displacement (IVV), computed as the coefficient of variation of the instantaneous speed-time data for horizontal axis; (ii) difference between the maximal and minimal hip velocity within the stroke cycle (dv); (iii) propelling efficiency, as the ratio between average swimming speed squared and hand speed squared ($np = \frac{u2}{v2}$) (Toussaint et al., 2006).

To assess motor control, the index of coordination (IdC) was assessed by measuring the lag time between the propulsive phases of each arm, expressing the percentage of the overall duration of the stroke cycle (Chollet et al., 2000). Following these authors, the arm propulsive phases begins with the start of the hand's backward movement and it ends at the moment where it exists from the water (pull and push phases), and the non-propulsive phase initiates when the hands releases from the water and ends at the beginning of the propulsive phase (recovery, entry and catch phases). For the front crawl technique, three coordination modes are proposed (Chollet et al., 2000): (i) catch up, when a lag time occurs between the propulsive phases of the two arms (IdC < 0%); (ii) opposition, when the propulsive phase of one arm starts and other arm ends its propulsive phase (IdC = 0%); and (iii) superposition, when the propulsive phases of the two arms are overlapped (IdC > 0%). To determine the accuracy of the digitizing procedure, two repeated digitization of a randomly selected trial were selected, and the coefficients of repeatability with 95% agreements limits were calculated using Bland and Altman method for each variable of interest: (i) 0.00835 m/s [-0.0071 to 0.0098] for the horizontal hip's velocity; (ii) 0.0022 m [-0.0026 to 0.0035] for hip's horizontal displacement; and (iii) horizontal hand's velocity 0.00996 m/s [-0.0091 to 0.0113]; (iv) 5.32º [-4.52 to 6.81] for trunk inclination.

Statistical Analysis

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

Results

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

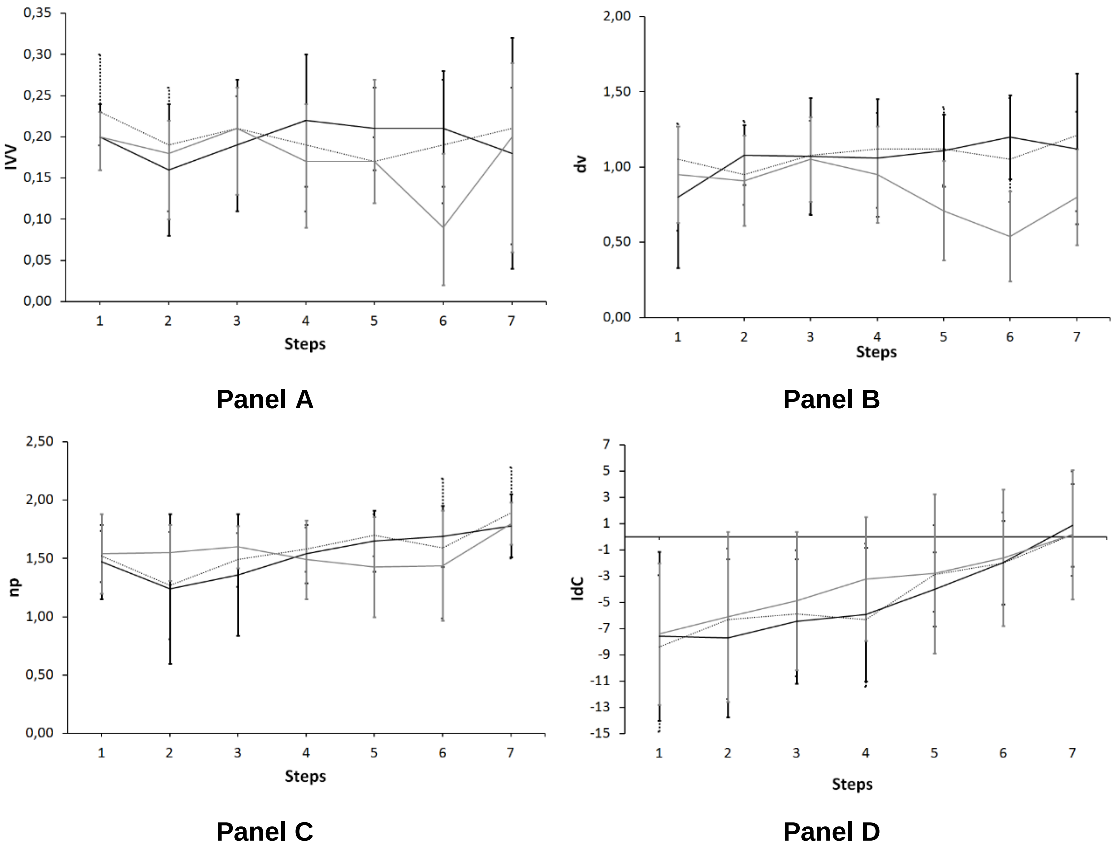

Figure 2. Median and interquartile range for the selected variables during 200 (black solid line), 300 (black dotted line), and 400 m (grey solid line) step lengths of an incremental front crawl protocol.

Discussion

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

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

In addition knowing that since long time, a meaningful effort has been done to assess and understand the mechanisms underlying swimming efficiency (e.g. Barbosa et al., 2008; Toussaint et al., 2006) and the inter-limb coordination (Figueiredo et al. 2013; Seifert et al. 2010), the present study selected those parameters aiming to highlight some technical issues for swimming performance, and, therefore, for control and evaluation, as well as for researches purposes.

In the current study, it was observed that, the swim efficiency and arm coordination behaviors were similar, along the three protocol variants to what have been reported in the literature for the incremental protocols with nx200 m. Some estimators suggest a change in the swimming efficiency (Seifert et al., 2010; Zamparo et al., 2005) and, IdC increases (Figueiredo et al., 2013; Komar et al., 201). So, the replication (an essential part of the scientific activity) of the 7x200 m protocol was achieved.

Notwithstanding the novelty and pertinence of the current research, some limitations should be pointed out. As it was performed a 2D kinematics assessment, and as swimming is a typical 3D motion movement (Figueiredo et al., 2013), some precaution should be taken when extrapolating this conclusions to some more detailed 3D kinematics. Moreover, to assess the swimmer's displacement and velocity, it was considered the hip instead of the centre of mass, although nowadays is well established between ~3% and ~7% bias for the displacement and velocity of those anatomical landmarks, respectively (Fernandes et al., 2012). Finally, some new insights about the response of the motor control variables (e.g. the neuro-muscular activity) were not took in consideration.

Conclusions

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

Acknowledgments

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Chapter 3

Which are the best sampling intervals VO_2 sampling intervals to characterize low to severe swimming intensities?

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Abstract

Cardiorespiratory response in swimming has been used to better understand aerobic performance, especially by assessing oxygen uptake (VO_2). The current study aimed to compare different VO_2 time-averaging intervals throughout low to severe swimming intensities, hypothesizing that VO_2 values are similar for different time-averages at low-moderate and heavy swimming intensities, but not for the severe domain. 20 male trained swimmers completed an incremental protocol of 7 x 200 m until exhaustion (0.05 $m \cdot s^{-1}$ increments and 30 s intervals). VO_2 was measured by a portable gas analyser connected to a snorkel system. 6 time-average intervals (breath by breath and 5, 10, 15, 20 and 30 s) were compared for all the protocol steps. Breath by breath and 5 s average exhibited higher VO_2 values than averages ≥10 s for all swimming intensities ($P \leq 0.02$; partial $\eta^2 \leq 0.28$). VO_2 values did not differed between 10, 15, 20 and 30 s averages throughout the incremental protocol ($P > 0.05$; partial $\eta^2 \leq 0.05$). Furthermore, 10 and 15 s averages showed the lowest VO_2 mean difference (0.19 $ml.kg^{-1}.min^{-1}$). For the six time-average intervals analysed, 10 and 15 s averages were those that showed the lowest changes on VO_2 values. We recommended the use of 10 and 15 s time averaging intervals to determine relevant respiratory gas exchange parameters along a large spectrum of swimming intensities.

Key words: swimming, incremental protocol, oxygen uptake, sampling intervals

Introduction

The dynamic behaviour of pulmonary gas exchange, particularly oxygen uptake (VO_2), during exercise has been traditionally studied through treadmill running, cycling and skiing incremental protocols (Chidnok et al., 2013; Midgley et al., 2007), but also in swimming (Fernandes et al., 2008). A common feature of these protocols is the endeavour to determine variables associated with aerobic performance, such as ventilatory threshold and maximal oxygen uptake (VO_2max) (Poole et al., 2008), typically involving stages of ~3 to 6 min with small intensity increments in-between. Researchers have concluded that shorter step length (i.e. ~3 min) is sufficient for the stabilization of VO_2 and blood lactate concentrations values (Chidnok et al., 2013; Kuipers et al., 2003), emphasizing its widespread use for the physiologic monitoring of athletes (Chidnok et al., 2013; Fernandes et al., 2011).

Specifically in swimming, the use of an incremental protocol of 2 to 3 min steps (i.e. 200 m length), conducted in actual swimming conditions, is not a new subject in what concerns swimmers' physiological evaluation (Barbosa et al., 2008; Fernandes et al., 2006; Fernandes et al., 2008; Reis et al., 2012a; Reis et al., 2012b., Roels et al., 2005). The respective protocol provided an important interpretation of traditional physiological variables, such as ventilatory and lactate threshold (Fernandes et al., 2011; Roels et al., 2005), VO_2max (Fernandes et al., 2006; Reis et al., 2012a; Reis et al., 2012b) and energy cost of exercise (Barbosa et al., 2008; Fernandes et al., 2006), as well as a contemporary analysis of the VO_2 kinetics at different swimming intensities (Reis et al., 2012a; Reis et al., 2012b). Relevant studies have used a portable metabolic system equipped with O_2 and CO_2 analysers, allowing breath by breath measurement (Cosmed K4b2, Rome, Italy) that is considered a crucial insight into the airways and lung mechanism, and gas exchange and pulmonary circulation (Robergs et al., 2010) since it enables the acquisition of data with greatest temporal resolution (Duffield et al., 2004; McLaughlin et al., 2001).

In the last decade, a respiratory snorkel and valve system adapted for Cosmed K4b2 apparatus was created and validated (Baldari et al., 2013; Gayda et al., 2010). Using these equipment the swimmers easily carry this breathing apparatus during in-pool protocols, with little mechanical constraints encumbering their normal swimming technique (Baldari et al., 2013; Gayda et al., 2014). The breath-by-breath gas analyser and the breathing snorkels are significant technological advances, allowing assessing in actual swimming conditions and in real time the cardiopulmonary responses in a wide range of exercise intensities (Baldari et al., 2013; Barbosa et al., 2010; Gayda et al., 2010). However, the selection of breath-by-breath leads to some technical errors (like noise caused by large inter-breath fluctuation in tidal volume and respiratory frequency, time delay of the expiratory tube, swallowing, coughing and sighing (Fernandes et al., 2012; Gayda et al., 2010; Reis et al., 2010), which might contribute to a great imprecision of the physiological VO_2 response (Robergs et al., 2010). Fernandes et al. (2012) proposed to minimize these constraints for swimming at the VO_2max intensity, using multiple analysis strategies, fundamentally by averaging across breaths and discrete time intervals, as previously applied for running and cycle ergometer exercise (Astorino, 2009; Hill et al., 2003; Midgley et al., 2007; Myers et al., 1990; Özyener et al., 2011).

The sampling interval technique is considered one of the most important VO_2 response analysis strategies (Astorino, 2009), being applied to assess a steady state or kinetics within a wide range of exercise intensities. By conducting an incremental protocol from moderate to severe running intensities, researchers analysed the effect of breath-by-breath fluctuations on the VO_2 response, observing that a true steady state can be determined when a time-average up to 30 s was used (Myers et al., 1990; Whipp et al., 1982). In opposition, Özyener et al. (2001) observed that the 10 s time-average interval was the most appropriate to characterize the VO_2 kinetics during a cycle ergometer incremental exercise. Specifically at severe intensity exercise, when the VO_2 response continues to increase until VO_2max is attained (Chidnok et al., 2013; Jones et al., 2010), the role of the sampling interval on VO_2 values is of great interest (Astorino, 2009;

Robergs et al., 2010). Astorino (2009) reported that the time-averaging interval could crucially affect the determination of running VO_2max, recommending the use of short time-averaging intervals (≤ 15 s), but Midgley et al. (2007) stated that longer averages (30 s) provide the best compromise to determine the most reproducible running VO_2max. In addition, when studying the interaction effect between the test duration and the time-average intervals on mean peak VO_2 values in cycling, it was noted that applying > 15 s time-average intervals in shorter test lengths leads to exclude VO_2 values when they are still increasing (Hill et al., 2003).

Specifically in swimming, the selection of the most appropriated time-averaging method to remove the significant variability imposed by breath-by-breath VO_2 has remained neglected when assessing a wide range of exercise intensities. In fact, only Fernandes et al. (2012) analysed the effect of various time-averaging intervals on VO_2, by focusing on the VO_2max variability, concluding that, when comparing breath-by-breath and averages of 5, 10, 15, 20 and 30 s, the 10 s time-average allowed the highest value for the VO_2 "plateau". However, as swimming competitive events are swum in a wide range of intensities (not only at the VO_2max intensity), in the current study it was aimed to compare short and long time-averaging intervals during swimming at low to severe intensities. It was hypothesized that the VO_2 values would be similar for all time-averages studied, when performing at low, moderate and heavy swimming intensities, but that at severe swimming intensities the VO_2 values would be higher when using short time-averaging intervals, particularly ≤ 15 s.

Material and Methods

Participants

Twenty well trained male swimmers (mean ± SD: age 18.8 ± 3.3 years old, body mass 72.7 ± 5.8 kg, height: 1.78 ± 0.06 m, fat mass: 10.6 ± 2.1%, training background: 10.5 ± 3.6 years and 114 ± 1.10 s of their best performance in the

200 m front crawl in 25 m pool) volunteered to take part in the current study. The local research ethics committee approved the research in accordance with the IJSM standards (Harris & Atkinson, 2013) and the subjects provided an informed consent. All the swimmers trained at least eight times per week and competed regularly in swimming freestyle events in National Championships for at least five years before the experiments. The subjects come to the swimming pool in a rested state, without previous (24 h) strenuous exercise. All subjects were familiarized with the testing procedure and equipments.

Experimental design protocol

The experimental protocol took place in a 25 m indoor swimming pool (1.90 m deep) with similar environmental conditions (mean ± SD: water temperature 27.3 ± 0.1º C, room temperature 28.5 ± 0.2º C and humidity 55.2 ± 0.4%) and time of day (between 8:00 am to 12:00 pm). After a moderate intensity warm-up of 20 min duration, swimmers performed a front crawl intermittent incremental protocol specific for swimming VO_2max assessment, consisting of 7 x 200 m (in-water starts and open turns), with increments of 0.05 $m{\cdot}s^{-1}$, and 30 s resting intervals, until voluntary exhaustion (Fernandes et al., 2008; Fernandes et al., 2011). The speed of the last step was established according to each swimmer's 400 m front crawl time at the moment of the experiments, and successive 0.05 $m{\cdot}s^{-1}$ were subtracted from that target, allowing the determination of the mean target speed for each step (for a more detailed description of the protocol validity (cf. Fernandes et al., 2011). To help maintaining the pre-defined individualised paces, a visual pacer with flashing lights (GBK-Pacer, GBK electronics, Aveiro, Portugal) was placed on the bottom of the pool, and measured the elapsed time with a chronometer (Seiko base 3 chronofrequencemeter).

Data collection

Respiratory gas exchange during the incremental protocol was assessed breath-by-breath with a portable telemetric gas analyser (Cosmed K4b2, Cosmed, Italy) connected to a validated respiratory snorkel and valve system (Aquatrainer, Cosmed, Italy). For a more detailed description and developing process, see (Baldari et al., 2013).

The K4b2 apparatus was calibrated following a standard certified commercial gas preparation (cf. “K4b2 use manual” Cosmed Ltd., 2011 44-47). The K4b2 portable unit measured the atmospheric pressure and ambient temperature, with the relative humidity manually reported to the K4b2 before each test. In addition, at the end of each 200 m step, the temperature of the expired air detected at the turbine was measured with an infrared thermometer (Kramer, Med.Ico). Heart rate (HR) was also recorded, at rest and every 5 s during the protocol, using a polar HR belt that transmitted the data to the K4b2 portable unit. All the collected data were telemetrically transmitted from the K4b2 portable unit to a PC and controlled in real time.

Capillary blood samples (25 µl) for blood lactate concentrations [La^-] analysis were collected from the ear lobe at the resting period, immediately after the end of each step, and at 3 and 5 min during the recovery period (Lactate Pro, Arkay, Inc, Koyoto Japan). This analyser was previously considered to be accurate and reliable (Baldari et al., 2009), and is used frequently for swimming research (Baldari et al., 2013; Fernandes et al., 2011; Fernandes et al., 2012).

In addition, after the end of each step, the subjects were immediately asked for their degree of perceived exertion (RPE) which was scored using the Borg’s RPE scale (Borg et al., 1987).

Data analysis

VO_2 data was analysed for all the incremental protocol, dividing its steps by low to moderate, heavy and severe intensity (cf. Burnley & Jones, 2007). In the low to moderate domain, the 1st to 4th steps that are under (or at) the lactate threshold boundary. The lactate threshold was assessed through the [La^-] vs. velocity curve modeling method, assumed as the interception point of the best fit of a combined linear and exponential pair of regressions (Fernandes et al., 2008; Fernandes et al., 2011). For the heavy intensity domain it were considered the 5th and 6th steps of the incremental protocol, which are above the lactate threshold but below the swimming velocity that allows VO_2max. The final step of the test, coincident with the VO_2max intensity, defined the severe intensity domain. VO_2max was considered to be reached according to primary and secondary traditional physiological criteria (Poole et al., 2008), particularly the occurrence of a plateau in VO_2 ($\leq$ 2.1 ml·kg^{-1}·min^{-1}) despite an increase in swimming velocity, high levels of [La$^-$] ($\geq$ 8 mmol·min^{-1}), elevated respiratory ratio (R $\geq$ 1.0), elevated heart rate [90% (220-age)] and an exhaustive perceived exertion that was controlled visually case by case (Fernandes et al., 2008; Fernandes et al., 2011). The swimming intensity domains are graphically

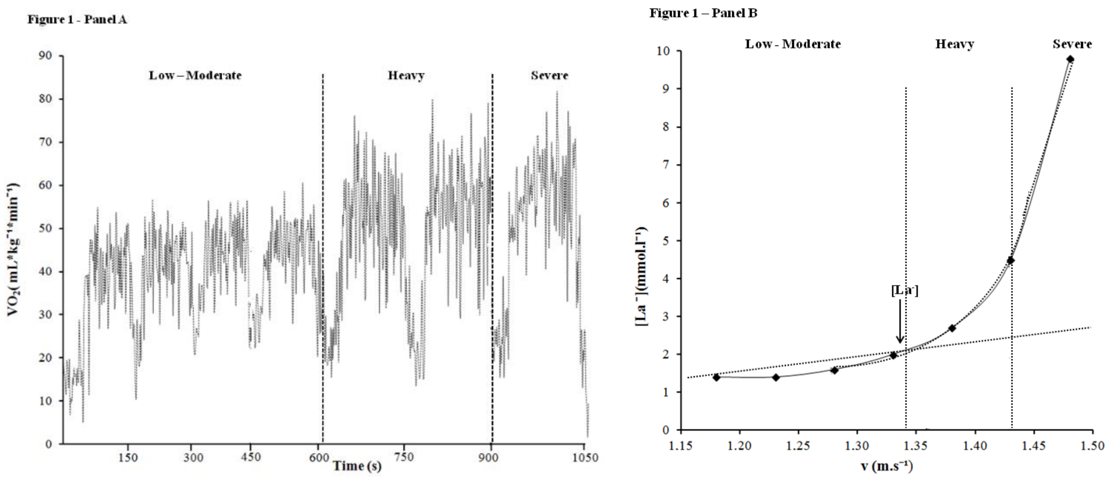

Figure 1. Individual breath-by breath response VO_2 uptake during the incremental swimming protocol. The swimming intensities are also displayed.

Individual VO_2 breaths were excluded due to occasional errant breaths caused by swallowing, coughing, sighing, signal interruptions and so forth (Baldari et al., 2013; Fernandes et al., 2012) that typically arise as a result of some constraints caused by the respiratory snorkel and valve system and by swimming proper characteristics (e.g. longer apnea moments during the turns).

In addition, values greater and lower than ± 4 SD from the local mean were omitted Özyener et al. (2001). To ensure a true VO_2 steady state, the last min of each step was smoothed at 3 breaths and averaged at 5, 10, 15, 20 and 30 s using the time-averaging function of the Cosmed analysis software. The temperature of the expired gas detected at the snorkel turbine was reported a posteriori to the Cosmed software to adjust volumes (cf. Baldari et al., 2013). Complementary, test-retest variability of the VO_2 values was calculated for all intensities of the incremental protocol and expressed as a coefficient of variation (CV), equal to 0.24, 0.21 and 0.22 for low to moderate, and heavy and severe swimming intensity domains (respectively). In addition, for each subject, it was calculated the signal to noise ratio of the breath-by-breath data, being moderate for all swimming intensities.

Statistical analysis

The 20 participants performed 143 trials of 200 m front crawl swimming. Ordinary least products regression was conducted to identify the closeness of correlation between the time-averaging intervals analysed and to observe if there was fixed or proportional bias between them (Ludbrook, 2010). Briefly, if the 95% confidence interval (CI) for the intercept *a* includes the value 0 there is no fixed bias, and if the slope *b* includes the value 1 there is no proportional bias. The distribution normality was checked with the Shapiro-Wilk test for all time-averaging intervals, and, to identify the significance of VO_2 changes across different time intervals throughout the incremental exercise. A repeated measure ANOVA and the assumption of the sphericity were tested (SPSS 19.0). As this assumption was not violated, no further adjustment values were required. *Post hoc* comparisons were conducted with pair-wise multiple comparison Sidak test. The effect size used was partial eta-squared (η^2), derived from one-way ANOVA. A *P* value of ≤ 0.05 was accepted to define statistical significance.

Results

Mean ± SD values of blood lactate concentration and heart rate at the 1st, 2nd, 3rd, 4th, 5th, 6th and 7th steps of the incremental protocol are displayed in Table 1.

Table 1. Mean ± SD values of blood lactate concentration and heart rate assessed in each step of the incremental protocol.

Variables	1st step	2nd step	3rd step	4th step	5th step	6th step	7th step
$[La^-]$ ($mmol \cdot l^{-1}$)	1.37 ± 0.33	1.40 ± 0.35	1.86 ± 0.85	3.10 ± 1.15	4.59 ± 0.97	6.67 ± 1.11	8.26 ± 1.21
HR (bpm)	131 ± 2.93	147 ± 2.59	153 ± 2.49	160 ± 4.62	165 ± 3.67	172 ± 2.33	187 ± 0.95

Table 2 shows the relationships between the different VO_2 time-averaging intervals using the coefficient of determination (r2), slope (b), intercept (a) with 95% CI of the ordinary least products regression equation, the mean difference and the P value of the comparison between the VO_2 values assessed with the breath-by-breath, 5, 10, 15, 20 and 30 s time-averaging intervals. For all pairs of VO_2 time-averaging intervals, the VO_2 values showed a high correlation (r2 > 0.90) and the ordinary least products regression analysis did not report fixed and proportional bias since a and b 95% CI included 0 and 1, respectively.

Table 2. Ordinary least products regression equation data for the comparison between time-averaging intervals (breath by breath and 5, 10, 15, 20 and 30 s averages). For this table are reported the values of Pearson's determinant correlation coefficient (r^2), slope (with 95 % CI), intercept (with 95 % CI) and the mean difference (with 95 % CI).

X vs Y n = 143	r^2	*b*	lower CI (*b*)	upper CI (*a*)	*a*	lower CI (*a*)	Upper CI (*a*)	Mean diff	Lower CI	Upper CI
bxb vs 5s	0.97	0.98	0.95	1.01	0.43	-0.80	1.63	0.31	-.004	0.62
bxb vs 10s	0.97	0.97	0.95	1.00	0.25	-1.16	1.62	0.73	0.37	1.08
bxb vs 15s	0.96	0.97	0.93	1.00	0.43	-1.16	1.97	0.92	0.51	1.32
bxb vs 20s	0.94	0.98	0.94	1.02	-0.46	-2.29	1.30	1.18	0.71	1.64
bxb vs 30s	0.92	0.98	0.93	1.02	-0.51	-2.71	1.58	1.34	0.78	1.89
5 vs 10s	0.99	0.99	0.97	1.01	-0.18	-1.04	0.66	0.42	0.20	0.63
5 vs 15s	0.97	0.98	0.96	1.01	0.01	-1.25	1.23	0.61	0.29	0.92
5 vs 20s	0.96	1.00	0.97	1.03	-0.89	-2.37	0.55	0.87	0.50	1.24
5 vs 30s	0.95	1.00	0.96	1.04	-0.76	-2.55	0.96	0.61	0.17	1.06
10 vs 15s	0.98	0.99	0.96	1.01	0.19	-0.96	1.31	0.19	-0.10	0.48

10 vs 20s	0.96	1.00	0.97	1.03	-0.71	-2.23	0.76	0.45	0.08	0.83
10 vs 30s	0.95	1.00	0.96	1.04	-0.76	-2.55	0.96	0.61	0.17	1.06
15 vs 20s	0.97	1.01	0.98	1.04	-0.90	-2.24	0.41	0.26	-0.07	0.59
15 vs 30s	0.95	1.01	0.97	1.04	-0.95	-2.68	0.72	0.42	-0.01	0.85
20 vs 30s	0.98	0.99	0.97	1.02	-0.06	-1.25	1.10	0.16	-0.14	0.46

Note: X vs Y, comparison between time-averaging intervals; bxb, breath by breath; r2, correlation coefficient; b, slope; a, intercept; CI, confidence interval.

Figure 2 evidences the VO_2 response in a representative subject of the sample (within the spectrum of swimming intensities analysed) for the most used time-averaging intervals. It is highlighted the contrast between (A, B, C and D panels, respectively): (i) breath-by-breath and 5 s averages; (ii) breath-by-breath and 20 s averages; (ii) 5 and 20 s time-averaging intervals; and (iii) 10 and 15 s time-averaging intervals.

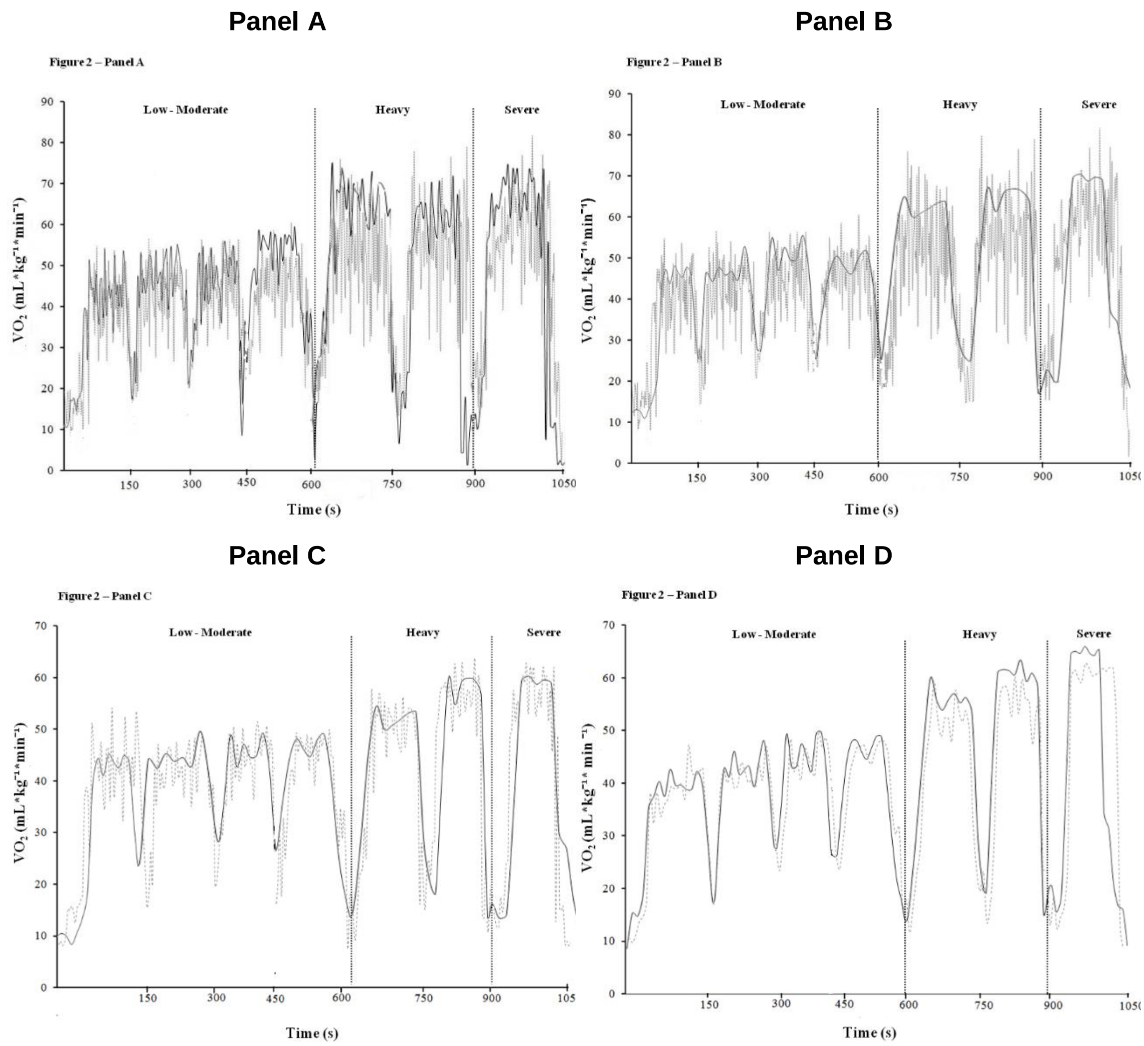

Figure 2. VO_2 response of a representative subject of the sample, where the contrast between the most time-averaging intervals used in swimming were evident. Breath-by-breath and 5 and 20 s averages (Panel A and B, respectively), 5 and 20 s averages (Panel C) and, 10 and 15 s averages (Panel D). On the panel A and B the breath-by-breath was represented by dashed line and 5 and 20 s averages by a solid line. On the panel C, the 5 s average was shown by a dashed line and the 20 s average by a solid line. On the panel D the 10 s average was represented by a dashed line and 15 s average by a solid line.

Table 3 shows the comparisons between VO_2 time averaging-intervals for low to moderate, heavy and severe swimming intensity domains. At all the swimming intensities, breath-by-breath and 5 s average presented higher VO_2 values than 10, 15, 20 and 30 s averages. 10, 15, 20 and 30 s averaged VO_2 values were similar.

Table 3. Results of repeated measures ANOVA on VO_2 values from low to severe swimming intensities. For this table are reported the values of F test (*F*), degrees of freedon (*df*), *P* values and partial eta-squared (η^2).

Swimming Intensity	Factor (time-averaging intervals)	F	*df*	*P*	Partial (η^2)
Low - Moderate	bxb, 5s, 10s, 15s, 20s, 30s	2.74	5	0.02	0.11
(VO_2 > 40 ml.kg^{-1}.min^{-1})	10s, 15s, 20s, 30s	0.13	3	0.93	0.01
Heavy	bxb, 5s, 10s, 15s, 20s, 30s	6.66	5	0.00	0.16
(40 < VO_2 < 55 ml.kg^{-1}.min^{-1})	10s, 15s, 20s, 30s	1.73	3	0.16	0.05
Severe	bxb, 5s, 10s, 15s, 20s, 30s	6.69	5	0.00	0.28
(VO_2 > 55 ml.kg^{-1}.min^{-1})	10s, 15s, 20s, 30s	0.44	3	0.72	0.02

Discussion

Although protocols of 2 to 3 min step lengths have already provided important insights concerning traditional physiological variables (Barbosa et al., 2008; Fernandes et al., 2008) and VO_2 kinetics (Reis et al., 2012a; Reis et al., 2012b) in swimming, the effect of different sampling strategies on gas exchange data requires optimization. As the selection of proper sampling intervals is unanimously recognized in other cyclic sports (Astorino, 2009; Hill et al., 2003; Midgley et al., 2007; Myers et al., 1990), swimming researchers should also attempt to find out which is the best sampling solution to reduce VO_2 values variability in a wide spectrum of exercise intensities. This study is the first to reach that goal, i.e., to accomplish a detailed methodological description of the time-averaging intervals influence on the VO_2 response at low to severe swimming intensities.

First, it is pertinent to consider the accuracy of the measurement equipment used in the current study. The $K4b^2$ apparatus has been seen as an accurate and reliable (Baldari et al., 2012; Gayda et al., 2010; McLaughlin et al., 2001), and the exclusion of occasional breaths values over ± 4SD VO_2 values from the local mean significantly minimized occasional errant breaths in assessing VO_2 values due to swallowing, coughing, sighing or some other reason unrelated to the physiological response of interest (Fernandes et al., 2012; Özyener et al., 2001). In addition, the smoothing of individual breath-by-breath VO_2 responses using 3-breath moving average (Fernandes et al., 2012) allowed production of a standard weighted response at 5, 10, 15, 20 and 30 s sampling intervals, thereby reducing the "noise" and increasing the parameter estimation. Also, the Aquatrainer snorkel and valve system attached to the $K4b^2$ was successfully used for swimming (Baldari et al., 2013; Barbosa et al., 2010; Fernandes et al., 2012; Reis et al., 2010; Reis et al., 2012a; Reis et al., 2012b), allowing swimmers to perform their movements without restrictions (Baldari et al., 2013); moreover, according to the manufacturer, the snorkel used is light, hydrodynamic, ergonomic and comfortable.

The current findings did not confirm the hypothesis that when swimming at low to moderate and heavy intensities the VO_2 time-averaging intervals studied are similar. Also, that at severe intensity higher values are obtained for short sampling intervals (≤ 15 s). Conversely, at the above-referred swimming intensities, the VO_2 values were higher for breath-by-breath and 5 s average than for 10, 15, 20 and 30 s time-averaging intervals. Complementarily, at the severe intensity, the shorter time-average intervals (particularly 10 and 15 s samplings) presented similar VO_2 values when compared to 20 and 30 s averages. These findings are very relevant to the correct interpretation of VO_2 data of swimming research that aims to well define the proper response for training and/ or to evaluate other experimental conditions.

The VO_2 values obtained in low to moderate, heavy and severe swimming intensities, independent of using breath-by-breath and 5, 10, 15, 20 and 30 s time-averaging intervals (< 40, 40 < VO_2 < 55 and > 55 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively), were similar to those described in the literature for well-trained male swimmers (Fernandes et al., 2006; Fernandes et al., 2012; Reis et al., 2012a; Reis et al., 2012b) and lower than those observed for elite male swimmers (Fernandes et al., 2008). The blood lactate concentration values (between 1.37 to 8.26 $mmol \cdot l^{-1}$) and heart rate (between 131 to 187 bpm) obtained along the incremental protocol are also in accordance with the literature (Fernandes et al., 2006; Fernandes et al., 2008; Reis et al., 2012a; Reis et al., 2012b; Roels et al., 2005).

Comparing the different time-averaging intervals for all swimming intensities, the breath-by-breath and the 5 s average presented higher VO_2 values than time-average intervals ≥ 10 s, corroborating the studies conducted in treadmill running (Midgley et al., 2007; Myers et al., 1990) and cycling (Hill et al., 2003), and evidencing that short time-averaging intervals overestimate the VO_2 values, independently of the selected swimming pace. This was not expected, particularly for the low to moderate intensity domain, since steady–state exercise offers low breath-by-breath fluctuations in tidal volume and breathing frequency, exhibiting a better highlighting of the underlying VO_2 values (Burnley & Jones, 2007; Myers et al., 1990). In fact, when analysing moderate to severe running intensities, it was observed an increase in VO_2 values as time-averaging intervals shorten (ranging from 0.8 to 4.5 $ml \cdot kg^{-1} \cdot min^{-1}$ for 60 s and breath-by-breath samplings, respectively) (Myers et al., 1990). In addition, for cycling at different intensities, the use of 10 s (instead of breath-by-breath) sampling can increase the confidence of the cardiorespiratory parameters estimations by reducing the noise and increasing the values precision (Özyener et al., 2001).

The current results (cf. Table 2 and panels B, C and D of Fig 2) corroborates the existent literature on running and cycling incremental exercises, once the highest VO_2 mean difference was observed when comparing breath-by-breath and 5 s with 20 s time-averaging intervals (ranging from 0.87 to 1.18 $ml \cdot kg^{-1} \cdot min^{-1}$) and the lowest difference was found between 10 and 15 s time-averaging (0.19 $ml \cdot kg^{-1} \cdot min^{-1}$). Particularly in swimming, the breath-by-breath, and the 5 and 20 s time-averaging intervals have been adopted in studies that used incremental protocols aiming to assess the swimmers' energy cost (Barbosa et al., 2008; Fernandes et al., 2006; Komar et al., 2012). Thus, based on previous data and in our findings, it is suggested that the use of breath-by-breath and the 5 s time-average intervals do not well represent variations in O_2 loading in the lung or its utilization in the muscles during low to severe swimming intensities.

Specifically focusing on exercising within the severe intensity domain, some authors stressed the importance of well choosing correctly the VO_2 time-averaging intervals due to the greater fluctuations in breathing frequency and tidal volume that may affect the VO_2 leveling off at VO_2max (Astorino, 2009; Fernandes et al., 2012; Hill et al., 2003; Midgley et al., 2007; Myers et al., 1990). Furthermore, the sampling intervals techniques at severe intensity could help the researcher to discriminate between the individuals who attain or not a VO_2 plateau (Astorino, 2009; Fernandes et al., 2012). Up to now, only one study aimed to observe the differences among time-averaging intervals at this specific swimming intensity (Fernandes et al., 2012), being reported that the breath-by-breath, 5, 20 and 30 s time-averaging intervals might difficult identifying the VO_2 plateau incidence and confirming the relevance of the use of 10 and 15 s samplings to assess VO_2. Moreover, the breath-by-breath gas sampling induces a significant VO_2 variability since the measures of VO_2 became vulnerable to fluctuation in breath-by-breath mode of expiratory flow (Hill et al., 2003). Concomitantly, these authors stated that VO_2 values became dependent upon sample size, making the breath-by-breath the less appropriate time-average interval to assess VO_2max. Myers et al. (1990) observed that ~20% of the difference in VO_2max was attributed to differences in the method of sampling gas exchange data, and that the highest inter-breath fluctuations were greater as fewer breaths were included in the average. Combining the literature and the current data, we propose that 10 and 15 s time-averaging intervals are the best to use when aiming assessing VO_2max in swimming.

In fact, the most appropriated average method should be the best compromise between noise reduction and data precision (Fernandes et al., 2012; Hill et al., 2003; Robergs et al., 2010) and the strategy for optimal time intervals selection is an very important decision to better highlight the underlying physiological response and helping avoiding artificially high or low VO_2 values (Astorino, 2009;

Hill et al., 2003). In fact, we wonder if researchers and coaches assess the VO_2 values incorrectly, how could they be certain that swimmers will exercise at the proper swimming training intensities? Consequently, researchers must continue investigating the most reliable and appropriate time-averaging intervals for the posed physiological questions, with special attention given to female swimmers, since in other sports, larges differences between genders were found for VO_2 values when using different sampling intervals (Astorino, 2009; Hill et al., 2003).

Conclusions

It is consensual that the optimal time-averaging interval provides the best compromise between the accuracy and the reliability for VO_2 evaluation. The current study provided some novel findings regarding the VO_2 response when using different time-averaging intervals during a large swimming intensity spectrum. A significant alteration on VO_2 values is associated with short time-averaging intervals (≤ 5 s) and a low variation is obtained by using ≥ 10 s time-averaging intervals. We recommend the use of 10 and 15 s time-averaging intervals to assess more precisely the VO_2 values in swimming incremental protocols aiming for exercise intensities prescription.

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Chapter 4

The effects of intensity on VO_2 kinetics during incremental free swimming.

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Abstract

VO_2 dynamics assessment in swimming, comprising a wide spectrum of exercise intensities, has evident potential to serve as a tool for training diagnosis. However, its study along different swimming intensities is inexistent. We aimed to assess and compare the VO_2 kinetics throughout low-moderate, heavy and severe swimming intensities, hypothesizing that its related parameters differ in-between intensity domains. Twenty male trained swimmers completed an incremental protocol of 7 x 200 m front crawl until exhaustion (0.05 $m \cdot s^{-1}$ increments and 30 s intervals), with VO_2 continuously measured by a portable gas analyser connected to a respiratory snorkel and valve system (Cosmed, Italy). VO_2 kinetics was assessed using a double exponential regression model giving the traditional VO_2 related parameters both for the fast and slow components. From low-moderate to severe swimming intensities changes occurred at 1st and 2nd VO_2 amplitudes ($P \leq 0.04$), time constants ($P = 0.01$) and time delays ($P \leq 0.02$). At the heavy and severe intensity domains, a notable VO_2 slow component (> 255 $ml \cdot min^{-1}$) appeared in all swimmers. VO_2 kinetics whilst swimming at different intensities offers relevant information regarding training and competitive stress that could be useful for training prescription (particularly for building more appropriated series) and subsequent performance enhancement.

Key words: gas exchange, oxygen uptake kinetics, exercise, intensity domains, front-crawl, modeling.

Introduction

Oxygen uptake (VO_2) kinetics analysis has been proposed as a useful tool for swimming training and diagnosis (Fernandes & Vilas-Boas, 2012; Reis et al., 2012b), particularly to better understand tolerance to exercise and the effect that traditional parameters of physiological function (i.e., anaerobic and ventilatory thresholds, maximal oxygen uptake (VO_2max) and efficiency/economy indicators (Bentley et al., 2007; Hill, 2014) have on the VO_2 response during exercise (Rodríguez et al., 2003; Reis et al., 2012a; Sousa et al., 2011).

Traditionally, the analysis of VO_2 kinetics parameters (i.e., amplitude/s, time constant/s and time delay/s) are used to characterize the VO_2 dynamics in the low-moderate, heavy, severe, and extreme exercise intensities (Poole & Jones, 2012). The low-moderate exercise intensity includes all power outputs below (and at) the lactate threshold (LT) boundary, with VO_2 obtaining a steady state (Robergs, 2014) and no change (or only a transient increase) in blood lactate (La) concentrations (Burnley & Jones, 2007; Carter et al., 2002). The heavy intensity displays power outputs above the LT, starting with a notable slow component (VO_2SC), leading to a higher VO_2 amplitude (Pessoa Filho et al., 2012; Pringle et al., 2003; Reis et al., 2012a) and eliciting a significant lactate accumulation as a function of time (Burnley & Jones, 2007). For the severe intensity, the exercise is significantly higher than LT, neither VO_2 nor lactate values can be stabilized (Gaesser & Poole, 1996), showing a pronounced VO_2SC and a greater lactate accumulation time compared with the previous intensity (Burnley & Jones, 2007; Pringle et al., 2003).

Over the last 90 years, VO_2 kinetics in the above-referred exercise intensities were well documented in exercise in the cycle ergometer and, less frequently, in treadmill running (see e.g., Jones & Burnley, 2009), but evaluations carried out in free swimming conditions (i.e., not in swimming flume) are very scarce. Since the pioneer work of Rodríguez et al. (2003), who investigated the VO_2 kinetics during the 100 and 400 m front crawl within the extreme intensity domain, some recent studies also considered the VO_2 response in swimming pool conditions focusing on the heavy or severe intensities (e.g. Fernandes et al., 2008; Pessoa Filho et al., 2012; Sousa et al., 2014). Despite this, and knowing that the swimming training process encompasses a wide range of exercise intensities, it seems relevant to evaluate and compare the VO_2 kinetics during different intensities, particularly including those above the LT, but also within the low-moderate exercise domain.

The comparison of VO_2 kinetics across different exercise intensity domains is not novel in running and cycling (Carter et al., 2000; Koppo et al., 2004; Pringle et al., 2003), and helped exercise physiologists and coaches identifying how VO_2 related parameters related to training and performance. For example, Carter et al. (2000) showed that well trained runners achieved short time-constant values (i.e., a fast stabilization on VO_2 values) during incremental exercise, indicating an evident effect of endurance development on initial VO_2 adjustments. Thus, findings about the parameters of dynamic VO_2 response, such as the amplitude and time constant of the fast component (and the slow phase, when existing) obtained across different exercise intensities, could be of great interest for a better definition of the bioenergetical training zones and to a more precise series building.

As no research comparing the VO_2 kinetics along a wide range of swimming intensities has been done, we used a discontinuous incremental protocol to analyse and compare the VO_2 kinetics within the low-moderate, heavy and severe exercise intensities. Based on cycling and running exercise studies conducted at these intensities (e.g. Carter et al., 2002; Koppo et al., 2004), we hypothesized that little or no changes on VO_2 kinetics (neither the appearance of a slow component) would be observed in different velocity bouts within the low-moderate intensity domain, whereas the time constant and time delay values would be noted within the heavy and severe intensity domains. Moreover, it was expected a notable increase in the fast and slow component amplitudes in the most intense intensities, i.e. in the last steps of the incremental protocol, significantly above LT.

Methods

Participants

Twenty well trained male swimmers (mean ± SD: age 18.8 ± 3.3 years old; body mass 72.7 ± 5.8 kg; height 178.2 ± 6.0 cm; fat mass (InBody230 Co., Ltd, USA) 10.6 ± 2.1%; training age 10.5 ± 3.6 years; and best 400 m front crawl performance in 25 m pool 243 ± 3 s) volunteered to participate in the study. Swimmers trained at least 8 times per week and competed regularly in freestyle events at the national level for at least 5 years prior to the experiments and were familiarized with the testing procedures. The local research ethics committee approved the research in accordance with the guidelines set forth by the WMA Declaration of Helsinki (2013). All participants (or parent/guardian when subjects were under 18 years old) provided an informed consent before data collection.

Testing

The participants were instructed to avoid high intensity training in the previous 24 h, and to abstain from food, caffeine, drugs, alcohol, and nicotine in the 3 h before testing. The experiments took place between 8:00 am to 12:00 pm in a 25 m indoor swimming pool (1.90 m deep) with constant environmental conditions (temperature: water 27.3 ± 0.1ºC, air 28.5 ± 0.2ºC; relative humidity 55.2±0.4%). After a 20 min low-moderate intensity warm-up, swimmers performed a discontinuous incremental front-crawl swimming test for VO2max assessment, consisting of 7 x 200 m swims with 0.05 m·s-1 increments and 30 s resting intervals between steps to voluntary exhaustion (Fernandes et al., 2011; Figueiredo et al., 2013). In-water starts and open turns without underwater gliding were used. The pre-defined speed of the last step was established according to each swimmer personal best time at 400 m front crawl at the time of the experiments. Then, 0.05 m.s-1 was successively subtracted, allowing the determination of the mean target speed for each step of the incremental protocol (for a detailed description of the protocol see Fernandes et al., 2012). To help maintaining the pre-defined individual speed, a visual pacer with flashing lights (GBK-Pacer, GBK-electronics, Aveiro, Portugal) was placed on the bottom of the pool. Manual timing was performed using a digital chronometer (Seiko, Tokyo, Japan).

Data collection

During the incremental protocol, respiratory gas exchange was assessed using a portable telemetric gas analyser (Cosmed K4 b^2, Cosmed, Italy) suspended over the water by a 25 m steel cable at 2 m height. This equipment was connected to the swimmer by a respiratory snorkel and valve system, specifically developed for aquatic exercise (Aquatrainer, Cosmed, Italy) (Baldari et al., 2013). The gas analyzers were calibrated before each test with gases of known concentration (16% oxygen and 5% carbon dioxide concentrations) and the turbine volume transducer was calibrated using a 3-l syringe according to the manufacturer's instructions. Ambient pressure and temperature were measured by sensors built in the portable unit, and the relative humidity was manually inputted before each test. During the end of each 200 m step, the expired air temperature detected at the turbine was measured with an infrared thermometer (Kramer Med, Inc, Italy). Heart rate (HR) was recorded at rest and every 5 s of the protocol using a Polar Vantage NV (Polar electro Oy, Kempele, Finland) that telemetrically emitted the data to the K4 b^2 portable unit.

Capillary blood samples were collected from the ear lobe at the resting period, immediately after the end of each step, and at the 3rd and 5th minutes of the recovery period for lactate (La) analysis (Lactate Pro, Arkay Inc., Kyoto Japan).

Data processing and modeling

Prior to analysis, the collected breath-by-breath VO_2 data were edited to exclude occasional errant breaths caused by swallowing, coughing, signal interruptions and so forth, and to improve the parameter estimation (Koga et al., 2005). First, values deviating more than 4 *SD* of the predicted regression value were considered as aberrant breaths and eliminated. Second, raw data were smoothed using a 3-breath moving average at 5 s intervals using the time-averaging function of the Cosmed analysis software (Fernandes et al., 2012). VO_2 data was analysed for each of the 7 steps of the incremental protocol and they were categorized as low-moderate, heavy and severe exercise intensities (Burnley & Jones, 2007; Poole & Jones, 2012) according to the loads corresponding to LT and VO_2max. First, a lactate-velocity curve modeling procedure was used to assess the anaerobic threshold (identified as LT) as the interception point of the best fit of a combined linear and exponential pair of regressions (Fernandes et al., 2011; Figueiredo et al., 2013). Second, conventional physiological criteria were used to identify VO_2max, namely, the occurrence of a plateau in VO_2 ($\leq$ 2.1 $ml \cdot kg^{-1} \cdot min^{-1}$) despite an increase in swimming speed, high levels of La_{max} ($\geq$ 8 $mmol \cdot l^{-1}$), elevated respiratory exchange ratio ($\geq$ 1.0), elevated HR [>90% (220-age)] (Poole et al., 2008). Then, taking LT and VO_2max as metabolic intensity indicators, the 1st to 4th steps were categorized as low-moderate intensity domain, as they were under (1st to 3rd) and at (4th step) the LT boundary (i.e. ~35 $ml \cdot kg^{-1} \cdot min^{-1}$). The 5th and 6th step were considered as heavy intensity, as they corresponded to an intensity above the LT and below the minimum swimming velocity corresponding to the VO_2max (Fernandes & Vilas-Boas, 2012) (i.e. 45 and 55 $ml \cdot kg^{-1} \cdot min^{-1}$), and the 7th step was considered as severe exercise, as it was coincident with the step in which VO_2max was attained (i.e. ~ 60 $ml \cdot kg^{-1} \cdot min^{-1}$).

To analyze pulmonary VO_2 kinetics, weight-related (relative) VO_2max data ($ml \cdot kg^{-1} \cdot min^{-1}$) were first modeled using a mono-exponential function:

$$VO_2(t) = VO_{2b} + A_1 * (1 - e^{-(t - TD_1/\tau_1)}) \qquad \textbf{(1)}$$

where VO_2 (t) represents the relative VO_2 at a given time *t*; VO_{2b} is the baseline, pre-exercise VO_2 (i.e. averaged for the 20 s before the start of the 200 m step); and, A1, TD1 and t1 are the amplitude, time delay and time constant of the on-transient VO_2.

In addition, a bi-exponential function was also explored to model the primary (Phase II) and slow (Phase III) components separately (Barstow et al., 1985; Rossiter, 2011):

$$VO_2(t) = VO_{2b} + A_1 * (1 - e^{-(t - TD_1/\tau_1)}) + A_2 * (1 - e^{-(t - TD_2/\tau_2)}) \qquad \textbf{(2)}$$

where VO_2 (t) and VO_2 are as in eq. (1); A1, TD1 and t1 are the amplitude, time delay and time constant of the primary component, respectively; and A2, TD2 and t2 are the corresponding parameters of the slow component.

The VO_2 response data were fitted to mono-and bi-exponential functions using a routine based on nonlinear least-square regression technique (lsqcurvefit) implemented in MATLAB R2010b (Mathworks, USA). The parameters of the model were estimated from the derived function. Additionally, the goodness-of-fit was judged by visual inspection of the residual plot.

Statistical analysis

Data are reported as mean values and standard deviations (±*SD*). The normality of distribution was checked with the Shapiro-Wilk's test. Before statistical analysis of the VO_2 kinetics parameters, the two nonlinear regression fits (i.e. mono- and bi-exponential) were compared for each step of the incremental swimming protocol using an *F*-test approximation. To compare the three swimming intensities, a repeated measures ANOVA was performed after checking for sphericity (Mauchly's test), and as this assumption was not violated, no further adjustments of the VO_2 values were required. Pairwise multiple *post hoc* comparisons were conducted with Bonferroni's correction. The level of significance was set at $P < 0.05$ (2-tailed).

Results

The *F*-test output showed homogeneity of variance when using the two nonlinear functions for low-moderate swimming intensity (P = 0.87), but differences were found for the heavy and severe intensity domains (P = 0.03); this led us to analyse the VO_2 kinetics using the double bi-exponential function for all 7-step exercise loads, as displayed in Figure 1 for a representative subject.

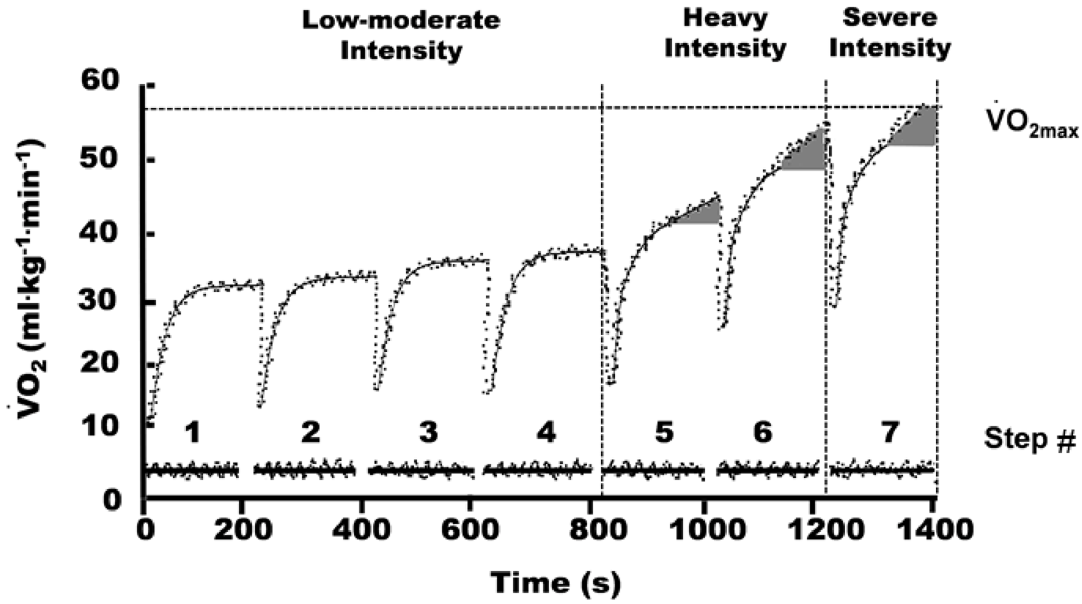

Figure 1. VO_2 kinetics of a representative subject along the 7-step incremental swimming protocol. Exercise intensity domains, VO_2max (dashed line), and VO_2 slow component (grey zone) are identified. The residuals plots of the measured (already smothed) and estimated VO_2 values for each step of the incremental exercise are presented bellow of each step.

Table 1 shows the VO_2 parameters estimated using the bi-exponential regression model, as well as HR and La, for each step of the incremental swimming protocol.

No significant differences were found among the estimated values for VO_2 amplitude, TD and t in the first four exercise loads corresponding to the low-moderate intensity domain ($P \geq 0.33$). Conversely, all VO_2 kinetics parameters in the later steps (5th, 6th, and 7th), corresponding to heavy and severe swimming intensities, differed for VO_{2b} ($F_{5,15}$ = 2.65, P = 0.02) and the rest of parameters of the primary and slow components: A1 ($F_{3,17}$ = 6.23, P = 0.01), A2 ($F_{5,15}$ = 6.61,

P = 0.02), TD1 ($F_{3,17}$ = 3.54, P = 0.04), TD2 ($F_{5,15}$ = 5.13, P = 0.02), t1 ($F_{5,15}$ = 5.22, P = 0.01), and t2 ($F_{3,17}$ = 3.25, P = 0.01). Thus, a faster VO_2 kinetics pattern became evident at the 5th and later steps with the appearance of an increased slow component (VO_2SC) superimposed on the faster primary response VO_{2p} (Δ VO_2 >250 ml·min^{-1}) (table 1, figure 1). As expected, HR and La values progressively increased and significantly higher while swimming at heavy ($F_{2,18}$ = 4.21, P = 0.02) and severe intensity domains ($F_{2,18}$ = 6.69, P = 0.03) compared with the low-moderate intensity loads.

Discussion

This study investigated the on-transient VO_2 kinetics during an incremental swimming test from rest to maximal exercise eliciting VO_2max across the low-moderate to severe intensity domains in competitive swimmers. The main findings were: 1) the VO_2 kinetics pattern remained stable within the range of intensities corresponding to the low-moderate domain (up to the LT boundary), reaching a steady state; and 2) conversely, across the heavy and severe exercise intensities (above LT), increasingly faster VO_2 kinetics shorter time constant and time delay values) and greater VO_2 gains in the primary component were noted, with the appearance of a noticeable slow component after ~130 s (ΔVO_2 > 250 ml·min^{-1}). As a central interpretation of this findings, one could argue that the changes observed in VO_2 kinetics parameters in the 6th and 7th steps of the incremental protocol might have been caused by the prior heavy exercise (i.e. 5th step) (Burnley et al., 2011; Jones et al., 2006), and not by the previous moderate steps (i.e. between the 1st and 4th steps) (Caritá et al., 2014; Sousa et al., 2014a).

The vast majority of studies in the field have been performed using cycle ergometer and provided important insights concerning the time-course of the VO_2 responses across a wide range of intensities (e.g., (Poole & Jones, 2012) for a review). Nonetheless, differences in the response across different exercise modalities (Jones & Burnley, 2005) and exercise intensity (Carter et al., 2002; Özyener et al., 2001; Rossiter, 2011) do exist. Our results, on the one hand, showed that the basic features of the VO_2 kinetics response low-moderate, heavy and severe in swimming are similar to the other modes of exercise, confirming the concept the VO_2 kinetics is modelated by the same fundamental mechanisms. On the other hand, though, differences arise, as this is the first study to provide detailed analysis of the VO_2 dynamics using a single incremental exercise protocol across a very wide range of intenisties in specific swimming conditions.

Currently, incremental exercise to the limit of tolerance remains by far the most widely used test to understand the integrated functioning of the cardiopulmonary and neuromuscular systems (Rossiter, 2001). Using this approach, researchers and coaches are able to assess several key physiological features useful for diagnosis and traning in swimming: aerobic fitness (Reis et al., 2012a), exercise tolerance (Burnley & Jones, 2007; Jones & Burnley, 2009), maximal aerobic power (Fernandes et al., 2003; Rodríguez et al., 2003), velocity at VO_2max (Sousa et al., 2014b), individual LT and ventilator threshold (Ribeiro et al., 2014; Rodríguez et al., 2003), energy cost of locomotion in water (Reis et al., 2010), and prediction of middle-distance (Reis et al., 2012b; Rodríguez et al., 2003) and sprint performance (Rodríguez et al., 2003). It was also showed that incremental protocols with 2 to 3-min steps are more suitable to the training and competitive necessities of swimmers and coaches (Barbosa et al., 2014; Fernandes et al., 2012).

In addition, the use of a double (instead of a single) exponential is also a relevant methodological issue in light of the recent debate about the most approprieated methods to quantify VO_2 dynamic responses (Robergs, 2014). In fact, fitting to a double exponential function has been accepted as a reliable mathematical method (Carter et al., 2000; Pringle et al., 2003; Reis et al., 2012a) that discriminates the different VO_2 components (Robergs 2014; Sousa et al., 2014b), although wheter each of the variables and parameters of the equation are system descriptors, with justifiable physiological equivalents, is currently by no means clear, particularly concerning the slow component (Whipp et al., 2005). For the current data, the double exponential function was found to better describe the amplitude of the slow component (which is a common observed physiological phenomenon when swimming at intensities around VO_2max) (Demarie et al., 2001; Fernandes et al., 2008; Sousa et al., 2014b).

Table 1. VO_2 estimated parameters extracted from the bi-exponential regression model in each step of the incremental swimming protocol. Heart rate, blood lactate concentration and time length of each of the steps are also shown.

	Low-moderate domain				Heavy domain		Severe domain
Step #	1	2	3	4	5	6	7
VO_2b (ml·kg^{-1}·min^{-1})	8±1$^{5-7}$	9±1$^{5-7}$	9±1$^{5-7}$	9±1$^{5-7}$	13±2^{6,7}	14±2^{7}	16±2
A_p (ml·kg^{-1}·min^{-1})	20±7$^{5-7}$	21±8$^{5-7}$	23±5$^{5-7}$	23±6$^{5-7}$	27±8^{6,7}	36±8^{7}	37±9
A_s (ml·kg^{-1}·min^{-1})	1±1$^{5-7}$	1±1$^{5-7}$	1±1$^{5-7}$	1±1$^{5-7}$	4±2^{6,7}	6±2^{7}	9±3
A_s (ml·min^{-1})	80±2$^{5-7}$	81±3$^{5-7}$	80±2$^{5-7}$	82±2$^{5-7}$	256±3^{6,7}	451±4^{7}	631±4
TD_p (s)	13±10$^{5-7}$	12±11$^{5-7}$	11±8$^{5-7}$	12±8$^{5-7}$	10±4^{7}	8±4	8±3
TD_s (s)	150±48$^{5-7}$	151±43$^{5-7}$	150±27$^{5-7}$	149±39$^{5-7}$	127±36^{7}	126±25	125±28
τ_p (s)	15±7$^{5-7}$	15±1$^{5-7}$	16±6$^{5-7}$	15±2$^{5-7}$	10±3^{7}	9±3^{7}	8±4
τ_s (s)	181±28$^{5-7}$	182±76$^{5-7}$	181±33$^{5-7}$	179±53$^{5-7}$	169±62^{6,7}	171±61^{7}	158±53
VO_2peak (ml·kg^{-1}·min^{-1})	34±1$^{5-7}$	36±2$^{5-7}$	37±2$^{5-7}$	38±3$^{5-7}$	45±2$^{6-7}$	55±2^{7}	58±2
Heart rate (beats.min^{-1})	131±3$^{2-7}$	147±3$^{3-7}$	154±3$^{4-7}$	161±5$^{5-7}$	165±4^{6,7}	172±2^{7}	188±1
La_{max} (mmol·min^{-1})	1.3±0.3$^{3-7}$	1.4±0.4$^{3-7}$	1.8±0.9$^{4-7}$	2.6±0.6$^{5-7}$	4.5±1.0^{6,7}	6.6±1.1^{7}	8.2±1.2
Time length (s)	177±3	170±3	163±3	156±3	153±4	148±3	140±3

Data are mean ± *SD*. VO_2b, baseline oxygen uptake; A_p and A_s, amplitude of the primary and slow components, respectively; TD_p and TD_s, time delay of the primary and slow components; τ_p and τ_s, time constants amplitude of the primary and slow component; VO_2peak, peak oxygen uptake; HR, heart rate; La_{max}, blood lactate concentration and time length of each of the steps. Superscripts, significantly different from noted steps (e.g., $^{5-7}$, different from steps #5 to 7; ^{5,,6,7}, different from # 5, 6, and 7) (ANOVA, Bonferroni's *post hoc* test, $P < 0.05$).

Focusing on the present results, similar VO_2 kinetics parameters were observed along the four protocol steps conducted within the low-moderate intensity, in line with studies conducted in other cyclic sports (Robergs, 2014).The VO_2 baseline values (~9 $ml \cdot kg^{-1} \cdot min^{-1}$ on average) showed a low variability, similar to previous results in well-trained swimmers (Reis et al., 2013) and in runners and cyclists (Capputo et al., 2004; Carter et al., 2000). The VO_2 amplitude during the firt four steps also showed low variability and were not different (Table 1), evidencing that swimming at low-moderate intensity induces a low blood flow and oxygen transport to active muscles (Mc Lean et al., 2010) despite an elevated respiratory work (Ogita & Tabata, 1992). The time constant values (~15 s on average) are in line with reports for swimming (Reis et al., 2013), running (Carter et al., 2000) and cycling (Pringle et al., 2003), indicating that well-trained can attain a VO_2 steady state within ~2 min of low-moderate intensity exercise (Figure 1), as shown by Robergs (2014). Likewise, the La_{max} values were not different among exercise intensities (between 1.3 and 2.6 $mmol.l^{-1}$) and are similar to previous results from the swimming literature (Fernandes et al., 2011; Roels et al., 2005; Reis et al., 2013). These suggest that at intensities at or bellow the lactate threshold, ATP resynthesis can be achieved via oxidative phosphorylation, a VO_2 steady state is attained and a low production and fast removal of lactate occurs, with a consequently low lactate accumulation (Mader et al., 1983; Burnley & Jones 2007). Lastly, the observed HR values were also in accordance with reference values (≤ 160 bpm) proposed for exercise intensity conducted at low-moderate intensity (Poole & Jones, 2005).

Comparison of VO_2 kinetics parameters in-between swimming intensities evidenced relevant differences from the 5th 200 m step onwards (i.e. heavy and severe intensity) (Table 1). First, the VO_2 baseline values were higher than those presented for running and cycling square wave exercises (Carter et al., 2002; Cleziou et al., 2004; Pringle et al., 2003), as frequently observed in swimming exercise (e.g., Fernandes et al., 2008; Reis et al., 2012a; Sousa et al., 2011). This is probably due to the fact that the swimmers wore the gas measurement apparatus (snorkel plus valve system attached to the portable $K4b^2$ unit) prior to enter the swimming pool and begin the exercise; moreover, during the 30-s rest intervals in-between steps, swimmers are not in a complete resting and stable position, as they stay in-water while adjusting the goggles, snorkel and mouthpiece and getting prepared for the following exercise bout. Therefore, these constraints would not allow the measurement of base line values of VO_2, as those typically reported for treadmill running and cycle ergometer testing exercise, and even as performing continuous protocols in a swim flume (e.g. Demarie et al., 2001; Faina et al., 1997).

Second, high values of the amplitude of the 1st exponential (A_p) were obtained after the 5th 200 m step of the incremental protocol, i.e. just after the LT boundary (in the beginning of the heavy intensity), in accordance to previous studies for the heavy and severe intensities (Carter et al., 2002; Pringle et al., 2003; Reis et al., 2012a). According to Carter et al. (2000) and Pringle et al. (2003) this increased amplitude can be due to the higher VO_2 demand since intensity and respiratory effort increase. This fact is observed in Figure 1 (heavy and severe intensity), where higher VO_2 values were reached at the primary phase of the exercise response. Third, the amplitude of the 2nd exponential (A_s) also increased significantly after the 5th step of the incremental protocol, concurrently with the magnitude of the exercise intensity and the appearance of the slow component (Demarie et al., 2001; Pringle et al., 2003; Reis et al., 2012a). In fact, the A_s has been commonly reported for heavy (Reis et al., 2012a), but mainly for severe swimming intensities (Billat 2000; Fernandes et al., 2008; Sousa et al., 2014b). However, when assessing A_s for a single exercise bout, Reis et al. (2012a) and Fernandes et al. (2008) reported values between 350 and 356 $ml \cdot min^{-1}$ for heavy and severe intensities, respectively, which were lower than the present values. Fourth, shorter time delays were noticed for heavy and severe intensity exercise than for low-moderate exercise. These findings are not consistent with previous studies in other cyclic sports that compared square wave exercises performed at low-moderate exercise. These findings are not consistent with previous studies in other cyclic sports that compared square-wave exercises performed on moderate and heavy (Carter et al., 2000) and moderate and severe intensities

(Cleziou et al., 2004), evidencing that the 30 s rest intervals in-between steps have some influence in the VO_2 kinetics during the following steps (Billat et al., 2002; Millet et al., 2003). Moreover the mean values observed in our study for the moderate, heavy and severe intensities were lower than those reported for running and cycling (Carter et al., 2002; Cleuziou et al., 2004; Pringle et al., 2003), but were similar with those reported in swimming (Pessoa Filho et al., 2012; Reis et al., 2013; Sousa et al., 2014b). This can be due to the fact that swimming is performed in a horizontal position, influencing the cardiorespiratory and metabolic demands compared to other land-based sports such as cycling and running (Aspenes & Karlsen, 2012). In fact, it has been suggested that exercising while in a horizontal position induces a lower sympathetic stimulation, VO_2 and HR values (Pluto et al., 1988).

Finally, we observed shorter time-constant values at the heavy and severe intensities compared with the low-moderate exercise intensity. These findings corroborate previous data for well-trained subjects exercising on the cycle ergometer (Cleuziou et al., 2004; Koopo et al., 2004) and on the treadmill (Carter et al., 2000; Millet et al., 2003). Previous work also suggested that this progressive decrease of the time-constant is related to the recruitment of different muscle fibers types responsible for force production (Koopo et al., 2004). Despite the appearance of an evdent slow component within the heavy and severe exercises, all thse studies suggest that at higher intensities swimmers would benefit more from a lower duration of each ste of exercise during aerobic training work. This would be due to the faster occurrence of the VO_2 fast component (lower time delay) and its stabilization (lower time constant). At lower intensities (within the low-moderate exercise, and in contrast to that traditionally suggested, the duration of the training series repetitions should be lower than 400 m, as the swimmers attain the VO_2 steady state within 2 to 3 min of exercise.

Study limitations

We must acknowledge that a single incremental test was performed which, together with the relative short duration of exercise compared to the longer exercise bouts usually investigated (6-7 min), could have led to a comparatively lower resolution and some uncertainty in parameter estimation. We need to emphasize that a discontinuous exercise protocol with 30 s rest periods between steps was performed. This implies that after the first step, an effect of previous exercise needs to be taken into consideration, and making comparisons with square-wave exercises is questionable. Therefore, when comparing different studies we have also take into consideration if they used and individual square-wave intensity or progressive intensities protocols. Lastly, it is also important to mention that step tests with set velocity increments do increase by a set power increment due to non-linear velocity-power relationships. Future experiments should be carried out trying to better characterize the underlying mechanism regarding the VO_2 dynamic behavior in different groups of swimmers and exercise conditions, as obvious differences on VO_2 kinetics parameters between groups were found when using different exercise types. Also exploring the extreme exercise domain, i.e. above VO_2max intensity, would be of particular interest.

Conclusions

The present findings showed that the fast and slow VO_2 components changed from low to severe swimming intensities (i.e. progressively greater VO_2 amplitudes and faster time constants) and that the well-known 7x200 m incremental protocol is suitable to assess these differences. Within the bouts performed at low-moderate intensity swimmers showed stability in all VO_2 kinetics parameters, whereas at the heavy and severe intensities, faster VO_2 kinetics and a pronounced VO_2 slow component occurred. Since swimmers typically train in a wide range of intensities, understanding how subtle VO_2 kinetics modifications in the most used bioenergetics training zones impacts on oxidative metabolism and performance might have important implications for optimizing training intensities prescription.

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Chapter 5

Reconstruction accuracy assessment of surface and underwater 3D motion analysis: a new approach.

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Abstract

This study assessed accuracy of surface and underwater 3D reconstruction of a calibration volume with and without homography. A calibration volume (6000 x 2000 x 2500 mm^3) with 236 markers printed on its surface (64 above water and 88 underwater control points – with 8 common points at water surface – and 92 validation points), was positioned on a 25 m indoor swimming pool and recorded with two surface and four underwater cameras. Planar homography estimation for each calibration plane was computed to perform the image rectification. Direct linear transformation algorithm for 3D reconstruction was applied, using 1600000 different combinations of 32 and 44 points out of the 64 and 88 control points for surface and underwater markers (resp.). Root Mean Square (RMS) error with homography transformation of control and validations points was lower than without it for surface and underwater cameras ($P \leq 0.03$). With homography, RMS errors of control and validation points were similar between surface and underwater cameras ($P \geq 0.47$). Without homography, RMS error of control points was greater for underwater rather than for surface cameras ($P \leq 0.04$) and the opposite was observed for validation points ($P \leq 0.04$). It is recommended that future studies using the 3D reconstruction should include homography to improve swimming movement analysis accuracy.

Keywords: biomechanics, kinematics, planar homography, 3D dual media reconstruction.

Introduction

The application of a multidigital camera set-up for three-dimensional (3D) analysis is frequently implemented in controlled indoor or laboratory settings (Bartlett, 2007; Silvatti et al., 2012a). However, its use outdoors or in constrained environments for specific sport applications is very limited (Silvatti et al., 2012b). Furthermore, in specific underwater conditions there are a number of technical issues (e.g. camera arrangement, calibration and protocol methodology, and motion data collection) that lead to a preference of a two-dimensional (2D) data collection (on one side of the body, assuming the existence of a bilateral symmetry; Psycharakis et al., 2005). This 2D approach might be less complex to use in traditional aquatic settings, but it implies a higher occurrence of errors by disregarding the multiplanar nature of the swimmers' movement characteristics (Figueiredo et al., 2011).

Complementarily, manual tracking is the most used method to detect and follow the trajectory of l body anatomical landmarks and calibration points (often attached to a custom static support recorded by each video camera field of view) during underwater movement quantitative analysis (e.g. de Jesus et al., 2012). With this process, the coordinates of the calibration points are registered in each camera 2D field of view, allowing a 3D movement reconstruction through the use of the direct linear transformation (DLT) algorithm (Chen et al., 1994). Previous findings revealed that the increase in number (e.g. from 8 to 20-24; Chen et al., 1994; Figueiredo et al., 2011; Psycharakis et al., 2005) and wider distribution (Challis, 2005; Chen et al., 1994) of the control points as well as the decrease in the calibration volume size (Gourgoulis et al., 2008; Lam et al., 1992) had improved the 3D reconstruction accuracy for surface and/or underwater cameras. Nevertheless, large calibration volumes are needed in swimming analysis since they minimize data extrapolation beyond the calibrated space, increasing further measurements accuracy (Psycharakis et al., 2010). Moreover studies have often reported larger errors for underwater camera views and have justified them through light refraction (water has higher refraction index than air) and consequently image deformation.

In addition, for a more accurate 3D reconstruction, the displacement of each pixel across the images (induced by camera, scene position and/or independent object-motion) should also be controlled (Alvarez et al., 2011; Alvarez et al., 2012; Chen & Chen, 2013; Nejadas & Linderbergh, 2014). For this purpose, homography is considered as a key step to obtain mappings between scene images, since computing homographies is faster and less erroneous than the motion process structure. This is justified by the fact that homography parameters are determined by few corresponding points (Alvarez et al., 2011; Nejadasl & Linderbergh, 2014) being typically estimated between images by finding feature correspondence. To the best of our knowledge, no research in swimming kinematics has considered the homography as a transformation method for 3D image rectification; we aimed to compare the 3D reconstruction accuracy in a large and static calibration volume (for surface and underwater digital video) using different calibration point sequences. The homography technique was applied to correct control points in each camera field of view and compared with the nonhomography implementation. Following Nejadasl & Lindenbergh, (2014), it was hypothesised that implementing homography technology would improve 3D reconstruction accuracy. Moreover, it is expected that, using homography or not, underwater cameras would display greater 3D reconstruction errors than surface cameras.

Material and Methods

Statistic 3D calibration volume

A 3D calibration volume was designed using the software Solid Works 2013 (3D CAD Premium, Dassault Systèmes SolidWorks Corporation, USA; Figure 1), being based on rigid structures used in previous swimming related studies (Figueiredo et al., 2011; Gourgoulis et al., 2008; Psycharakis et al., 2004).

Afterwards, it was built using a computer numerical control machine and was comprised of three blocks, each one with the following dimensions: (i) 2000 mm length, 2500 mm height and 2000 m width. These parts were framed and joined to form a rectangular prism of 6000 x 2500 x 2000 mm^3 (with a total calibration space of 30 x 109 mm3), enabling the recording of at least two complete consecutive swimming cycles. The 3D coordinate accuracy of the calibration volume was 1. 2 mm for horizontal (x) and vertical (y) and 1.4 mm for lateral axes (z).

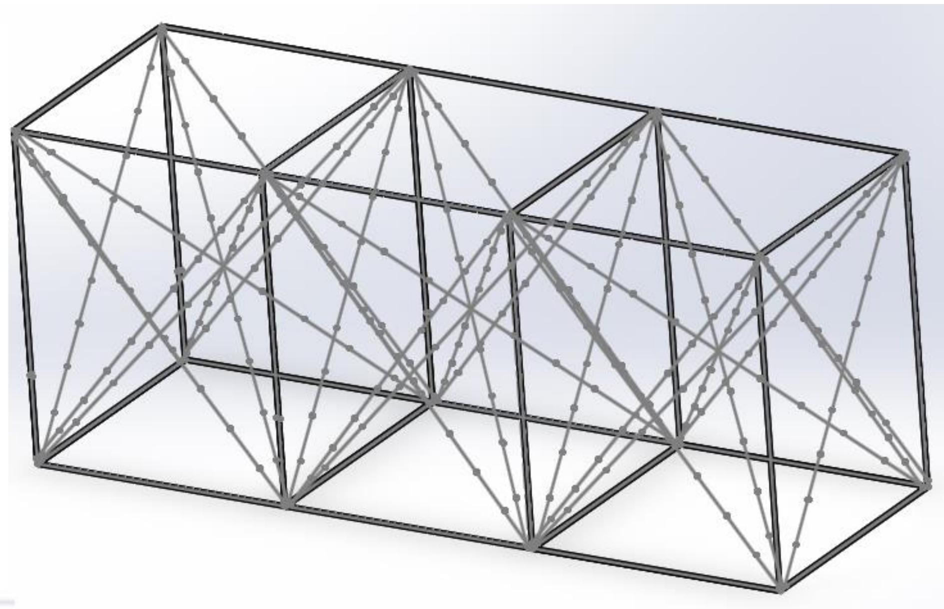


Figure 1. The rectangular prism used as the static calibration volume.

The calibration volume structure was manufactured in anodised aluminium with 25 mm diameter, selected on the basis of its high flexural stiffness relative to its weight, allowing reduced distortions due to frequent research use or/and to the swimming pool environment (Lingaiah & Suryanarayana, 1991). Stainless steel cables (5 mm) were used to triangulate each frame part, ensuring that the adjoining sides of the frame followed orthogonality. Two hundred and thirty-six black tape markers (15 mm width each) were attached with 250 mm separation on the aluminium tubes in the x, y and z axes. A laser device was used to improve the accuracy of markers placing (Nano, Wicked Lasers©, Hong Kong). The 3D coordinate marker accuracy was 0.5 mm for x and y and 0.9 mm for z.

Data collection

The 236 calibration points distribution in the calibration volume was registered simultaneously by four underwater and two surface water stationary video cameras (HDR CX160E, Sony Electronics Inc., Tokyo, Japan) recording at 50 Hz. The calibration volume was positioned in the centre of a 25 m swimming pool (1900 mm depth) and its longitudinal axis was aligned with the lateral wall of the swimming pool. Figure 2 shows the calibration volume and the 3D camera set-up: the surface and underwater cameras were placed at an equal distance from the respective centre, forming an angle of 100° between the axes of the two surface water cameras while the angle established by the underwater cameras varied between 75 and 110° (Figueiredo et al., 2011).

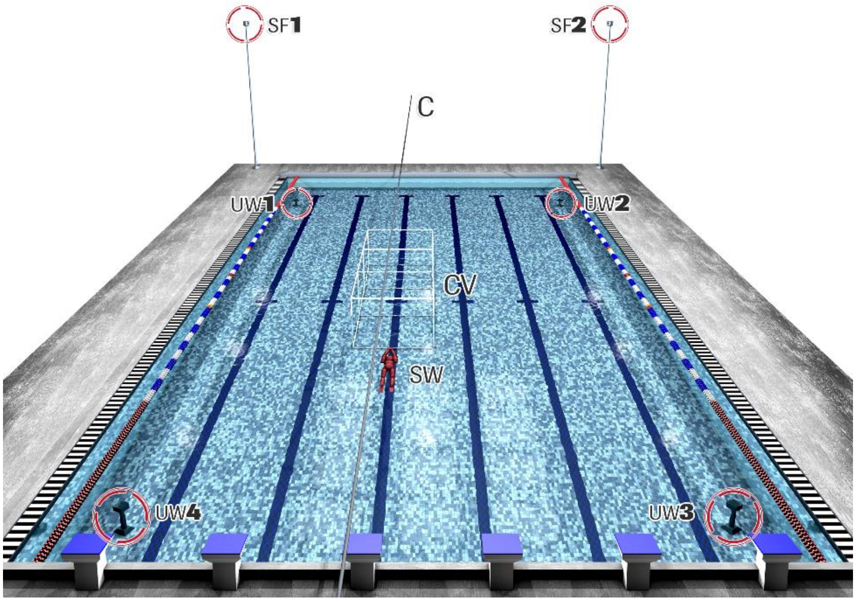


Figure 2. Experimental 3D cameras setup. Cameras UW1, UW2, UW3 and UW4: - 1st, 2nd, 3rd and 4th underwater cameras. Cameras SF1 and SF2: 1st and 2nd surface cameras. Calibration volume – CV. Swimmer-SW.

The surface cameras were positioned in tripods (Hamma Ltd., Hampshire, UK) at 3.5 m (height) and those underwater were maintained in a waterproof housing (SPK-HCH, Sony Electronics Inc., Tokyo, Japan) and fixed on tripods at 1.0 to 1.5 m (depth). A LED system visible in each video camera field of view was used for image synchronisation.

Data Analysis

The 236 points on the calibration volume with known coordinates were manually digitised (Matlab version R2012a, Mathworks, Inc.) to obtain their (u, v) coordinates and the DLT method was applied for 3D reconstruction according to Equation 1 (Abdel-Aziz & Karara, 1971).

$$u = \frac{L_1 x + L_2 y + L_3 z + L_4}{L_9 x + L_{10} y + L_{11} z + 1}$$
$$v = \frac{L_5 x + L_6 y + L_7 z + L_8}{L_9 x + L_{10} y + L_{11} z + 1} \qquad \textbf{(1)}$$

To evaluate the quality of manual digitization procedure, a specific routine in the Matlab software was developed to identify the difference between real and estimated coordinate values. The routine consisted in classifying the digitized points into large, medium and small errors, being: (i) large error, represented by red colour (error > 25 mm), (ii) medium error, represented by orange colour (15 mm < error < 25 mm) and (iii) small error, represented by green and blue colours (error ≤ 15mm). After this analysis, depending on the results obtained, the points were re-digitized until optimal value achievement. A limit of 25 mm for the difference between the real and estimated coordinates was imposed for each camera view and several points have showed errors in the range of 25 and 33 mm, which was a hint to the use of manual homography transformation to assign the real coordinates to each projected point, and to avoid possible mistakes.

Under linear projection, the mapping from a pixel (u, v) to a control point $(x, y, 0)$ on the calibration plane $(z = 0)$ is encapsulated by a homography matrix H as:

$$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = H_{3x3} \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{pmatrix} . \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} \qquad \textbf{(2)}$$

Given at least four point correspondences , the homography can be estimated by solving the over-determined homogeneous linear system.

$$\begin{pmatrix} u_1 & v_1 & 1 & 0 & 0 & 0 & -x_1u_1 & -x_1v_1 & -x_1 \\ 0 & 0 & 0 & -u_1 & -v_1 & -1 & y_1u_1 & y_1v_1 & y_1 \\ u_2 & v_2 & 1 & 0 & 0 & 0 & -x_2u_2 & -x_2v_2 & -x_2 \\ 0 & 0 & 0 & -u_2 & -v_2 & -1 & y_2u_2 & y_2v_2 & y_2 \\ u_3 & v_3 & 1 & 0 & 0 & 0 & -x_3u_3 & -x_3v_3 & -x_3 \\ 0 & 0 & 0 & -u_3 & -v_3 & -1 & y_3u_3 & y_3v_3 & y_3 \\ u_4 & v_4 & 1 & 0 & 0 & 0 & -x_4u_4 & -x_4v_4 & -x_4 \\ 0 & 0 & 0 & -u_4 & -v_4 & -1 & y_4u_4 & y_4v_4 & y_4 \end{pmatrix} \cdot \begin{pmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{31} \\ h_{32} \\ h_{33} \end{pmatrix} = 0 \quad \textbf{(3)}$$

The point correspondences are derived from the manually digitized calibration points and their real coordinates. Once the homography is estimated, a projected feature point detected at pixel (u_p, v_p) can be associated to its world coordinates according to Equation 2.

During the manual homography analysis the two camera sets (i.e. surface and underwater) were independent in-between, as shown in Figure 3.

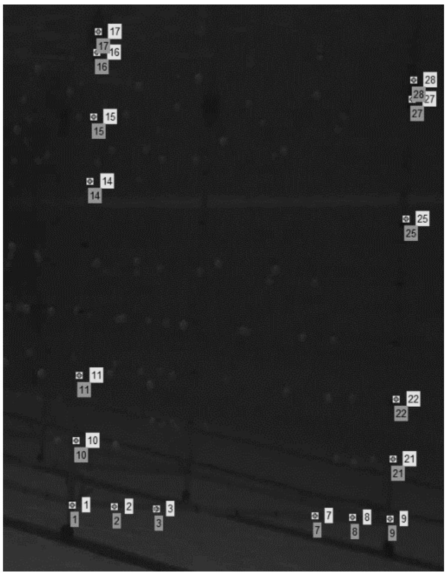


Figure 3. Visual comparison of 3D reconstruction for the homographic transform of a calibration frame.

Of the 236 points on the calibration volume with known coordinates located at the horizontal and vertical rods making the calibration volume, a total of 64 surface and 88 underwater markers near the frame inner and outer corners and at the water line were selected to be the control points (circles and diamonds in Figure 4). The points at the water line were common to both surface and underwater control points. The remaining 92 points (38 surface and 54 underwater) were used as validation points.

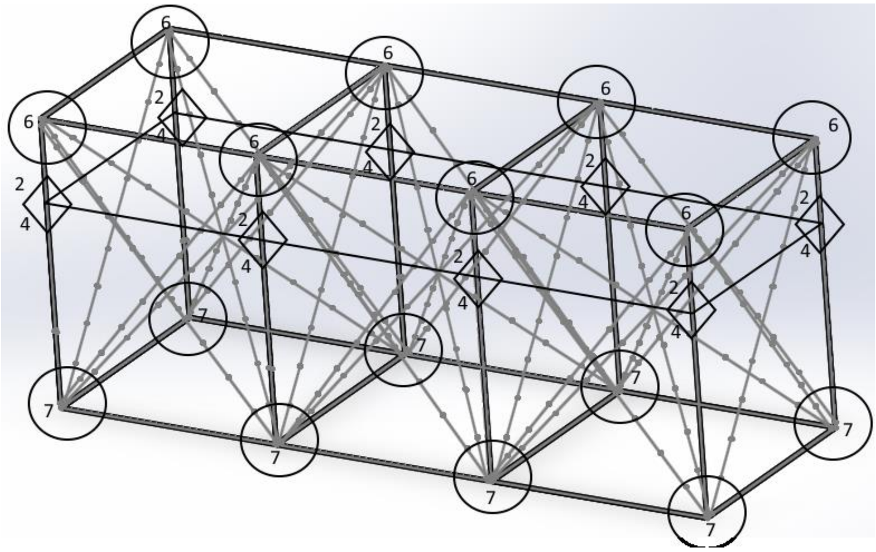


Figure 4. Location of the control points on the static calibration volume.

From each of those above-referred areas, points were systematically combined in sets of 3 per corner (whenever possible), resulting in sets of 40 and 48 calibration points for surface and underwater, respectively. From these calibration points, the DLT was performed and applied to the remaining control points and separately for the validation points.

Then, a new combination of calibration points from the control points was selected and a new DLT transformation was again performed and applied to the remaining points. This systematic selection procedure resulted in over 1.5 million different combinations for the underwater control points and over 1000 combinations for the surface control points.

When the homography transformation was used to smooth the digitizing errors, it was applied only to the control points and then the above-referred systematic selection procedure was used. To simplify, the homography transformation was applied to a plane defined by a given set of rods, for each camera separately, with the process being applied three times to each camera to account for the rods that are common to two planes. Validation points were also smoothed by the homography transformation; however these points will not be digitized in future uses of the calibration volume.

Accuracy

All reconstruction errors were calculated from the raw coordinate data, without any smoothing procedure (Scheirman et al., 1998), and determined by the Root Mean Square (RMS) error of the 92 validation points (for the total calibration volume), using the following equations:

$$X_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_{ni} - x_i)^2} \tag{4}$$

$$Y_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_{ni} - y_i)^2} \tag{5}$$

$$Z_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(z_{ni} - z_i)^2} \tag{6}$$

$$R = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[(x_{ni} - x_i)^2 + (y_{ni} - y_i)^2 + (z_{ni} - z_i)^2\right]} \tag{7}$$

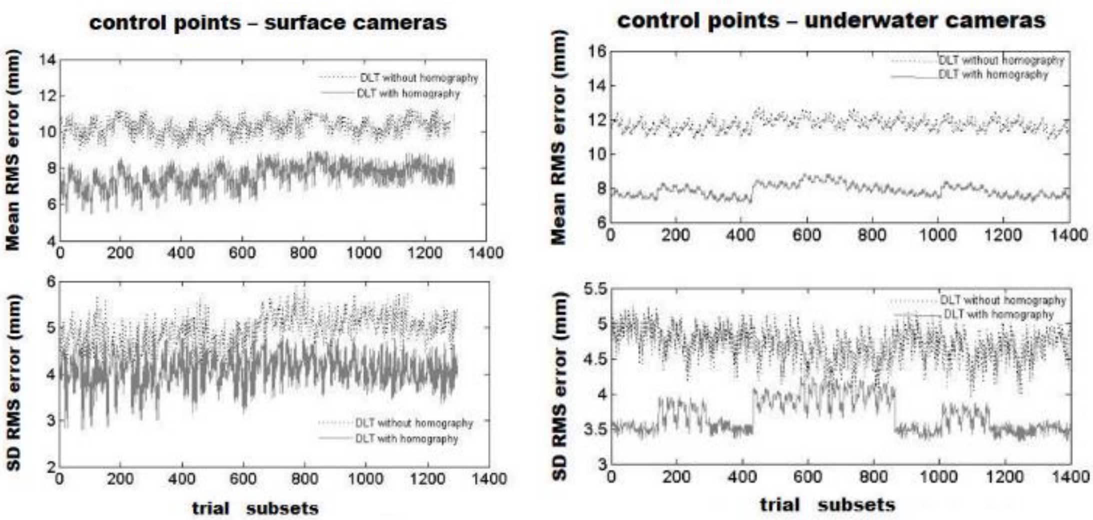
Where, X_r, Y_r, Z_r and R were the RMS errors for each axis and for the resultant error (respectively), x_{ni}, y_{ni} and z_{ni} were the real coordinates, x_i, y_i and z_i were the reconstructed coordinates and N was the number of points used.

Statistical analysis

Data are reported as mean and standard deviations (±*SD*). The normality distribution was checked and confirmed with Shapiro-Wilk's test. A two-way repeated measures ANOVA (homography x cameras) on control and validation points was performed after verifying sphericity (Mauchly's test). Pairwise multiple post hoc comparisons were conducted with Bonferroni's correction. The level of significance was set at α = 0.05 (2-tailed). All data were analyzed using the IBM® Statistical Package for Social Sciences (SPSS) 20.0.

Results

Figure 5 (a) and 5 (b) depicts the mean and SD values of RMS errors (mm) for 3D reconstruction of surface (over 1000 combinations of trial subsets of 40 points each from the set of 64 control points near the corners) and underwater cameras (over 1600000 combinations of trial subsets of 48 points each from the set of 88 control points near the corners) cameras with and without homography transformation. Considering reconstruction through control point sets, homography use has revealed lower RMS errors for surface and underwater cameras rather than without it, being 7.3 ± 4.5 vs. 10.5 ± 4.8 for surface ($P < 0.01$) and 7.7 ± 3.8 vs. 12.1 ± 5.1 for underwater views ($P < 0.01$). Surface and underwater cameras have shown similar RMS error with homography ($P = 0.47$), although, without it, RMS error was greater for underwater rather than for surface cameras ($P < 0.04$).

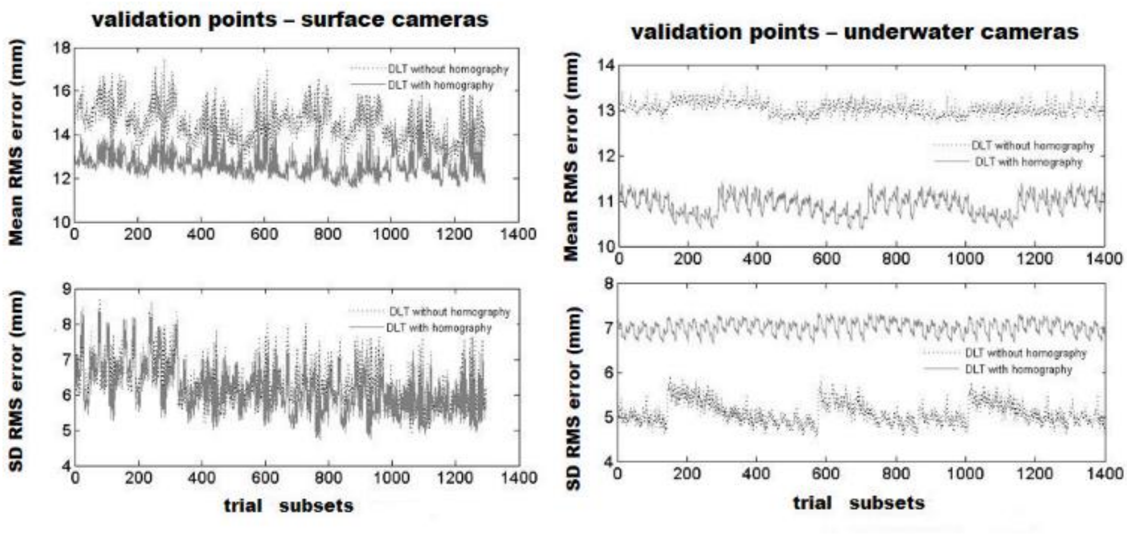


Panel A **Panel B**

Figure 5. (Panel A and B). RMS errors for the 3D reconstruction of surface and underwater cameras without (dotted line) and with homography (continuous grey line) transformation

obtained from subsets of 40/64 (surface) and 48/88(underwater) control points positioned on the horizontal and vertical corner rods. Trial subsets in the x axis represents the (arbitrary) ID of the simulation case with different subsets of control points.

Figure 6 (a) and 6 (b) depicts the mean and SD values of RMS errors (mm) for reconstruction of surface (38 validation points) and underwater (54 validation points) cameras with and without homography transformation. Regarding reconstruction through validation point sets, RMS error was lower with homography than without it for both cameras sets, being: 12.1 ± 6.5 vs. 15.9 ± 6.6 245 for surface ($P < 0.01$) and 10.8 ± 5.3 vs. 13.3 ± 6.7 for underwater views ($P < 0.03$). Surface and underwater cameras evidenced similar RMS errors with homography ($P = 0.49$), but without it, RMS reconstruction errors of surface were greater than underwater points ($P < 0.04$).



Panel A **Panel B**

Figure 6. (Panel A and B). RMS errors for 3D reconstruction with 92 validations points of the horizontal facets of surface (38 points) and underwater (54 points) cameras without (dotted line) and with homography (continuous grey line) transformation. Trial subsets in the x axis represents the (arbitrary) ID of the simulation case with different subsets of control points.

Discussion

Kinematic analysis in swimming imposes obstacles to data acquisition, particularly through the existence of errors associated to image distortion, digitalization and 3D reconstruction (Bartlett, 2007; Kwon & Caselbolt, 2006). Thus, it is crucial to observe its influence on the final results, analysing validity, reliability and accuracy (Scheirman et al., 1998). To the best of our knowledge, the current study is the first that has analysed the effects of homography and cameras positioning (surface/underwater) on 3D RMS reconstruction errors in swimming. Main findings were: 1) using homography, RMS errors of control and validation points were smaller than without homography use and remained similar between surface and underwater cameras and; 2) without homography, RMS errors of control points were greater for underwater rather than for surface cameras and, in opposition, RMS errors of validation points were greater for surface than for underwater cameras. These current findings partially confirm the already established hypotheses and suggest that, homography method applied for surface and underwater cameras is suitable to minimize the error magnitude provided by large calibration volume dimensions.

Literature pointed out that the number of control points and its respective distribution on calibration volume is determinant for 3D reconstruction accuracy of surface and underwater cameras (Challis, 2005; Chen et al., 1994; Figueiredo et al., 2011; Gourgoulis et al., 2008; Kown & Caselbolt, 2006; Psycharakis et al., 2005). In the current study, the number of control points number distributed on the corners and facets for surface and underwater cameras were quite larger than those usually reported in swimming related studies (de Jesus et al., 2012; Figueiredo et al., 2011; Gourgoulis et al., 2008; Psycharakis et al., 2005; Psycharakis et al., 2011). The use of 8 to 30 control points distributed at the horizontal and vertical rods is often used for swimming 3D reconstruction with shorter calibration volume dimensions (Figueiredo et al., 2011; Psycharakis et al., 2005) than those applied in the current study. Figure 4 revealed that the best set of control points was located on the corner and facets agreeing with previous study suggestions (e.g. Figueiredo et al., 2011). As calibration volume size increases, it has been recommended to increase the number of control points with proper distribution to ensure accuracy augmentation (Chen et al., 1997; Lauder et al., 1998; Psycharakis et al., 2005). Hence, researchers using static calibration structures with similar dimensions than those used in the current study should prioritize those criteria. Notwithstanding the number and location of control points as well as the calibration volume size relevance for better 3D reconstruction accuracy, (Chen et al., 1994; Lam et al., 1992), the effects of displacement of each pixel across the images induced by camera, scene position and/or independent object-motion should also be considered in swimming analysis, since they have greatly affected reconstruction in other sport scenarios (Alvarez et al., 2011; Alvarez et al., 2012; Nejadasl & Linderbergh, 2014). These drawbacks have been minimized through the use of different methods (Wang et al., 2005) being homography estimation well-accepted as a key step to obtain mappings between scene images providing less erroneous 3D reconstruction (Nejadasl & Linderbergh, 2014).

In the light of these benefits provided by homography technique, its use was tested in swimming and has revealed a decrease in RMS errors of control and validation points for surface and underwater cameras, corroborating previous findings considering reconstruction from multiple perspective views (Alvarez et al., 2011; Alvarez et al., 2012). For example, Alvarez et al. (2011) analysing competitive tennis have observed a reduction of ≥ 10 mm on RMS error of control points when using homography estimation, which was higher than the current findings. In the present study, a reduction of 3 to 5 mm on RMS errors for both control and validation points in surface and underwater views was considered quite relevant due, especially for underwater cameras, to video recording complexity in aquatic scenarios (Kwon & Caselbolt, 2006). Differences between Alvarez et al. (2011) study and the present study findings for surface RMS errors can be attributed to the greater incidence of light refraction and the smaller number of cameras used to record video images in swimming pool environment. Despite several previous findings considering underwater and surface 3D reconstruction analysis, the current study has evidenced that swimming researchers should focus on homography implementation to test present results replication on their specific 3D cameras arrangements.

The control points and calibration volume sizes have not been an exclusive research topic in swimming 3D reconstruction studies, being researchers also interested in comparing RMS errors between underwater and surface cameras (Figueiredo et al., 2011; Gourgoulis e al., 2008; Psycharakis et al., 2005). However, this problematic should not be considered as the major research concern, since specialized literature has evidenced greater underwater RMS errors rather than surface cameras prior to 1990s (e.g. Hay & Guimarães, 1983). Researchers should focus on methods that allow minimizing errors from estimated to real coordinates of each camera, as homography has demonstrated. Implementation of homography has provided similar RMS errors for surface and underwater cameras, and these findings suggest for these sets of points that homography can be considered more advantageous for underwater reconstruction. Without homography, surface reported lower RMS errors of control points than underwater cameras, as currently shown in literature (Figueiredo et al., 2011; Gourgoulis et al., 2008; Psycharakis et al., 2005). These authors displayed RMS errors ranging from 4.06 to 6.16 mm for surface and 4.04 to 7.38 mm for underwater cameras, which were lower than the current results and that can be explained by the differences in calibration volume sizes. Despite these differences, the large calibration volume used in the current study has presented acceptable RMS errors of control points for surface and underwater cameras, avoiding the need of extrapolation beyond the calibrated space (e.g. Gourgoulis et al., 2008). The greater RMS error for surface rather than in underwater cameras when considering validation points, suggest that, when homography is not used in large calibration volume dimensions, researchers should choose control instead validation points for surface reconstruction.

Further Considerations

Notwithstanding the originality and relevance of the current data, some considerations should be taken into account. First, static calibration volumes remain by far the most widely used for swimming 3D reconstruction, although promising alternative calibration methods as chessboard and moving wand, have shown interesting results (Silvatti et al., 2012a; Silvatti et al., 2012b). Nevertheless, these methods do not minimize extrapolation occurrence beyond the calibrated space, increasing measurements inaccuracy. The large calibration volume used in this study registered low and acceptable reconstruction accuracy errors to record at least two swimming cycles, but researchers are advised to take some cautions during video recording data collections. Second, manual digitization process implies systematic and random errors (Bartlett, 2007), however, in the current study they were kept in an acceptable level (≤ 8 mm) (Lam et al., 1992). Third, the large number of control points used in the present study for surface and underwater reconstruction allowed obtaining low RMS error for a large calibration structure, although it is acknowledged that a minimum of six non-coplanar control points well distributed over the calibration volume can preserve adequate accuracy. Six control points recommendation can simplify digitization process; however those points seem not enough to supply reliable reconstruction of large calibration volumes.

Conclusions

In the current study, the implementation of planar projective transformation through homography indicated that RMS reconstruction errors of a set of 40/64 (surface) and 48/88 (underwater) control points positioned on the orthogonal corners and facets of a calibration volume with 6000 x 2500 x 2000 mm were similar and acceptable for surface and underwater views. Based on these findings, future studies using large calibration volumes able to record at least two cycles of a given swimming technique should consider homography transformation to smooth the digitized control points and improve the DLT reconstruction accuracy.

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Chapter 6

Tridimensional kinematics of low to severe front crawl swimming.

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Abstract

Coaches are often challenged to optimize swimmers technique at different training and competing intensities, but its tridimensional (3D) analysis at a wide range of training zones was not carried out. We aimed to analyse front crawl 3D kinematics and inter-limb coordination at low to severe intensities swimming by observing eventual inter and intra-steps modifications. Ten male swimmers performed a light paced 7 x 200 m front crawl incremental protocol until exhaustion (0.05 $m.s^{-1}$ increments and 30 s intervals), with images from two cycles in each step (at the 25 and 175 m laps) being recorded by two surface and four underwater cameras. Metabolic anaerobic threshold (AnT) was also assessed using the lactate concentration/velocity curve modelling method. General swimming and segmental kinematics, and inter-limb coordination, changed from low to severe intensities ($P \leq 0.05$) and within the 200 m steps performed above the AnT (i.e. at, or closer to, the 4th step; $P \leq 0.05$). Concurrently, intracyclic speed fluctuations and propelling efficiency remained similar within the range of swimming intensities and within all the 200 m steps (independently of the swimming intensity; $P > 0.05$). Swimming intensity has a significant impact on swimmers segmental kinematics and inter-limb coordination, with modifications being more evident after the point when AnT is reached. As competitive swimming events are conducted at heavy and severe intensities (in which anaerobic metabolism becomes more prevalent), coaches should implement specific training series that lead swimmers to adapt their technique to overcome task constrains in non-homeostatic conditions.

Key words: biomechanics, video analysis, linear kinematics, angular kinematics, motor control

Introduction

In daily swimming practice, different front crawl intensities are used to adapt swimmers technique to successful race performance. Considering low to severe front crawl intensities, kinematical analysis evidences an increase of stroke frequency (SF) and decrease of stroke length (SL) (Fernandes et al., 2011; Psycharakis et al., 2008), a stabilization of intracyclic velocity variations (IVV) (Barbosa et al., 2015), a decrease of propelling efficiency (Barbosa et al., 2015; Komar et al., 2012), an increase of segmental kinematics (Barbosa et al., 2015; Komar et al., 2012) and increase of inter-limb coordination (IdC) (Barbosa et al., 2015; Figueiredo et al., 2013a; Komar et al., 2012) to satisfy task demands, particularly an inter-step speed increase in incremental exercises and an intra-speed maintenance in single bouts. These findings were observed through bidimensional (2D) analysis, with the most meaningful mechanical modifications occurring after the swimming intensity corresponding to the anaerobic threshold (AnT) (Fernandes et al., 2011; Figueiredo et al., 2013a). However, it is well known that the 2D approach hamper refined and accurate swimmers technical feedback, with tridimensional (3D) settings reducing kinematic biases (e.g. ~3 to 7% of speed differences between swimmers' hip and center of mass; Fernandes et al., 2012).

Up to now, the inter and intra-step effects on 3D front crawl kinematics during incremental swimming are unknown, with 3D related studies focusing on the mechanical changes within laps of single maximal front crawl bouts. When comparing the 1st and 4th 50 m laps of an all-out 200 m front crawl, although only one cycle was analysed (Figueiredo et al., 2013b; Psycharakis et al., 2010), it was observed relevant technical adaptations: a SF increase, a SL and propelling efficiency decrease, and an IVV stabilization (Figueiredo et al., 2013b; Psycharakis et al., 2010). Therefore, it is recommended that swimmers carefully manage their SF and SL to minimize IVV (Seifert et al., 2014), and to maximize propelling efficiency (Komar et al., 2012), using different upper and lower limb combinations. So, specifically in incremental swimming, it could be hypothesized that to comply with inter-step speed rise and within step speed requirements, swimmers would adapt their center of mass kinematics by adopting specific upper and lower limb movement strategies.

Furthermore, it has been reported that upper limb segmental kinematics are determinant for the maintenance of stable speed and/or IVV between laps of a maximal front crawl effort (Cappaert et al., 1995; Figueiredo et al., 2012a), being observed a horizontal hand speed increase and an elbow angle stability during the pull and push phases, accompanied by a stable horizontal center of mass speed (Figueiredo et al., 2012a). This ~90-120º elbow angle flexion maintenance is also considered determinant during incremental swimming since it contributes to successful propulsion (Cappaert et al., 1995; McCabe et al., 2011) and to reduced trunk obliquity, leading to shorter lower limb amplitude (and, consequently, to lower drag) and higher vertical feet speed, horizontal center of mass speed and propelling efficiency (Gatta et al., 2012; Payton et al., 2002; Zamparo et al., 2005). In addition, as upper and lower limbs actions are coupled with each other, inter and intra-steps kinematical changes could affect inter-arm coordination, mainly at intensities above AnT (Figueiredo et al., 2013a).

It seems consensual that for obtaining optimal responses to the continuous training process, regular incremental testing (including detailed biophysical assessments, i.e., a combined physiological plus biomechanical) analysis should be implemented. In fact, the training loads definition and implementation should not focus exclusively on volume and intensity, but also on swimmers' technical constraints (Figueiredo et al., 2014; Oliveira et al., 2012). Therefore, understanding the 3D kinematical profile of common training intensities would provide a proper guide for controlling the appropriateness of the swimming technique for low to severe training and competition paces. Our purpose was to analyse and compare swimmers' inter and intra-steps front crawl 3D kinematics along a well-stablished training control incremental protocol.

Methods

Participants

Ten well-trained front crawl male swimmers (age: mean ± SD: 19.78 ± 4.31 years, height: 1.78 ± 0.06 m, body mass: 71.40 ± 5.72 kg and arm span: 1.81 ± 0.07 m) voluntarily participated in the current study. Swimmers attended national and international level competitions on a regular basis, having 81.63 ± 2.71% of the 200 m freestyle short course World Record. Furthermore, all swimmers adopted six lower limb actions per upper limb front crawl cycle. The local research ethics committee approved the research in accordance with the Declaration of Helsinki and all participants (or parent/guardian when subjects were under 18 years old) provided an informed consent before data collection. Swimmers were instructed to refrain from high intensity training previously to the data collection and were required to report to the swimming pool in a rested state (fully hydrated and abstained from caffeine, alcohol, nicotine and other drugs 24 h before testing).

All participants were familiar with the testing procedures, as had been involved in previous similar evaluations. After receiving full explanation concerning the purpose of the study, swimmers were marked with black tapes with reflective points on the following anatomical landmarks: vertex of the head, ear lobe and (right and left) acromion, lateral humeral epicondyle, ulnar styloid process, third distal phalanx, prominence of great femoral trochanter external surface, lateral femoral epicondyle, lateral malleolus, calcaneus and hallux, favoring image viewing for further digitalization and 3D reconstruction.

Experimental testing design

The experiments took place in a 25 m indoor swimming pool (1.90 m deep), with constant environmental conditions (mean ± SD: water temperature 27.3 ± 0.1ºC, room temperature 28.5 ± 0.2ºC and humidity 55.2 ± 0.4%) and daytime (between 8:00 am to 12:00). Before the experiments, swimmers performed a 20 min low-moderate intensity warm-up. Since previous breathing action influences the magnitude of body roll in front crawl swimming (McCabe et al., 2012), participants were required to familiarize themselves with breath holding within the calibrated space located in the middle of the swimming pool. Testing consisted of a front crawl intermittent incremental protocol of 7 x 200 m (using in-water starts and flip turns), with increments of 0.05 m.s^{-1} and 30 s resting intervals between steps, until voluntary exhaustion (Barbosa et al., 2015; Fernandes et al., 2011). The pace of each step was controlled through a visual pacer (GBK-pacer, GBK-electronics, Aveiro, Portugal) with flashing lights on the bottom of the pool. The last step was predefined as the swimmer's best time at 400 m front crawl at the moment of the experiments and 0.05 m·s^{-1} was successively subtracted allowing the determination of the mean target speed for each step (Figueiredo et al., 2013a). In addition, elapsed time for each swim was hand-timed with a manual digital chronometer (Seiko, 140, Tokyo, Japan).

Data collection

Front crawl kinematics were analysed using 3D [horizontal (x), vertical (z) and lateral (y)] video recordings by two surface and four underwater stationary video cameras (HDR CX160E, Sony Electronics Inc., Tokyo, Japan), operating at a frequency of 50 Hz, with an electronic shutter speed of 1/250 s. Four underwater cameras, kept in a waterproof housing (SPK-HCB box, Sony Electronics Inc., Tokyo, Japan) at 0.95 m below the water surface, were positioned at 5.00 and 0.62 m away from the front and side walls (respectively) and the angle between the axes varied from 75 to 110º (de Jesus et al., 2015). Two aerial cameras, kept on a support at a height of 5.87 m, were positioned 2.10 and 1.06 m away from the front and side pool walls (respectively) and the angle between the lenses was ~100º. Six camera images were recorded independently and swimmers were monitored when passing through a specific pre-calibrated space using a calibration frame with orthogonal axes (6.0 x 2.5 x 2.0 m, for x, z and y directions) (Figure 1; de Jesus et al., 2015). Image synchronization was obtained using a pair of LEDs' under and over water surface (fixed to the calibration volume) visible in each video camera field of view.

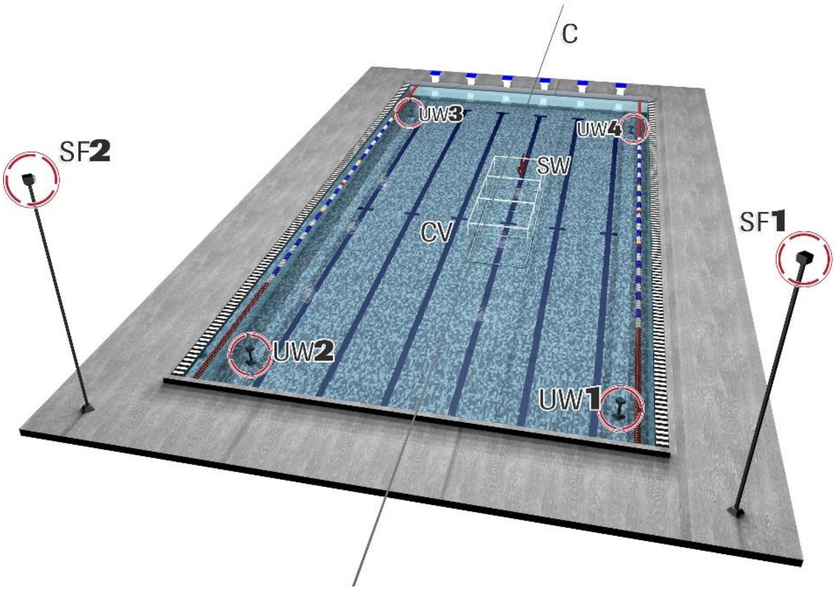

Figure 1. Schematic representation of the 3D experimental setup with surface cameras (SF1 and SF2), underwater cameras (UW1, UW2, UW3 and UW4), calibration volume (CV) and swimmer (SW).

Capillary blood samples were collected from swimmers' ear lobe at resting period, immediately after each step and at 3rd and 5th min of recovery period for lactate [La$^-$] analysis (Lactate Pro, Arkay Inc., Kyoto Japan). As an indicator of exercise intensity, AnT was assessed through [La$^-$] vs. velocity curve modelling method, assumed to be the interception point of the best fit of a combined linear and exponential pair of regressions (Fernandes et al., 2011; Figueiredo et al., 2013a).

Data processing

Front crawl kinematics of two consecutive swimming cycles was video captured in two different moments (the first and penultimate lap 25 and 175 m) of each 200 m step of the incremental protocol. Each one of the cycles was defined as the period in-between the two entries of the same hand (McCabe e al., 2012), with the mean values used in subsequent statistical analysis. Ariel Performance Analysis System 3D motion analysis software (Ariel Dynamics Inc., San Diego, CA, USA) was used to manually digitize the 20 anatomical landmarks separately for underwater and surface views following anthropometrical model (de Leva, 1996). To obtain a single file of the 3D object-space coordinates of the underwater and surface views, 24 points of the calibration frame were digitized and the direct linear transformation (DLT) algorithm was applied (Puel et al., 2012). All digitized data were smoothed using a recursive second order low-pass Butterworth digital filter, with a 5 Hz cut-off frequency after residual analysis. Root mean square (RMS) reconstruction errors of 21 validation points on the calibration frame, which did not serve as control points, were as follows (for x, y and z axis, respectively): (i) 2.96, 2.74, and 2.14 mm representing 0.10, 0.09 and 0.15% of the calibrated space for surface cameras; and (ii) 4.11, 5.02 and 3.11 mm, representing 0.12, 0.16 and 0.24% of the calibrated space for underwater cameras. Figure 2 illustrates 3D calibration volume with the specific location of control and validation points for underwater and surface cameras.

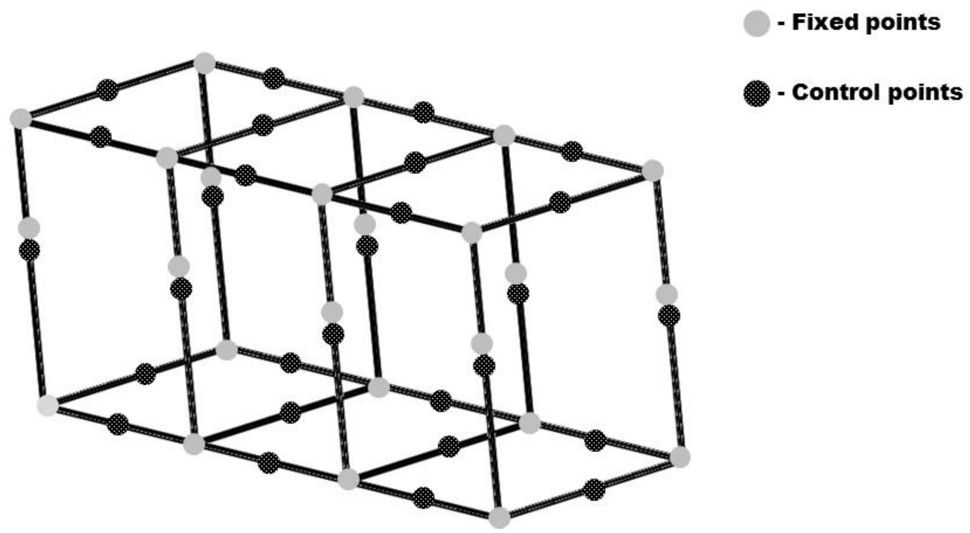

Figure 2. 3D calibration volume with the specific location of the control and validated points for underwater and surface cameras.

Data analysis

Front crawl technique was divided into four phases determined from swimmers' x and z positions of the third distal phalanx relative to the external reference frame and the acromion (Chollet et al., 2000; McCabe et al., 2011): (i) entry, between the first z negative until the first x negative coordinates of the third distal phalanx (catch); (ii) pull, from the catch until the mid-swimming cycle position (determined when the x position of the third distal phalanx is zero relative to the acromion);

(iii) push, from the end of the pull until the hands release from the water (determined by the first z positive coordinate of the third distal phalanx after the underwater trajectory release); (iv) recovery, from release until re-entry into the water of the third distal phalanx (determined by the first z negative coordinate of the third distal phalanx; cf. Figure 3).

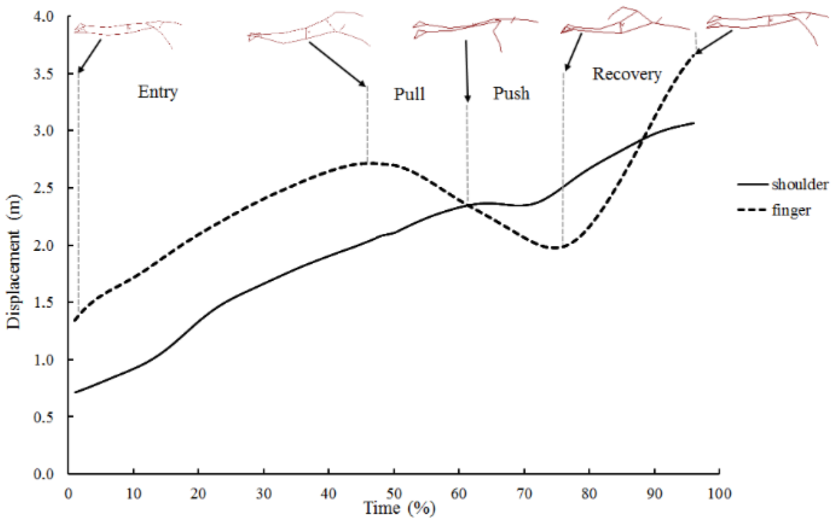

Figure 3. Definition of each front crawl stroke phase. Time was expressed as a percentage of the stroke cycle.

Table 1 describes the used methodologies of the front crawl 3D kinematic and inter-limb coordination parameters.

Test-retest reliability of the digitizing process was calculated through intraclass correlation coefficient (ICC) for the following variables: (i) 0.81 for horizontal center of mass speed; (ii) 0.94 for horizontal center of mass displacement; (iii) 0.96 for horizontal hand speed; (iv) 0.91 for vertical feet speed; (iv) 0.88 for trunk obliquity and (v) 0.92 for elbow angle.

Table 1. Description of the front crawl 3D kinematics and inter-limb coordination parameters.

Parameters	Description
General swimming kinematics:	
·**Stroke frequency**	The inverse of the time to complete one full swim cycle.
·**Stroke length**	The horizontal displacement of the whole body centre of mass during one swim cycle.
·**Speed**	The product of stroke frequency and stroke length.
Center of mass kinematics:	
·**Horizontal speed fluctuation of the centre of mass**	The coefficient of variation of the speed-time instantaneous data in the direction of the x (horizontal) axis.
·**Vertical speed fluctuation of the centre of mass**	The coefficient of variation of the speed-time instantaneous data in the direction of the z (vertical) axis.
Efficiency:	
·**Propelling efficiency**	Calculated according to the equation: $np = ((v0.9)/2\pi\ SFl))(2/\pi)$ being v the mean velocity of the swimmer, SF the stroke frequency, l the average shoulder to hand distance (assessed by APAS System measuring the upper limb length and the average elbow angle during the insweep of arm pull). The equation was adapted for the contribution of the legs, as originally proposed by Zamparo et al. (2005).
Segmental and anatomical kinematics:	
·**Right and left hip vertical amplitude**	The swimmer's average hip vertical displacement by the time required to complete one swim cycle.
·**Horizontal hands backward displacement**	The most forward and backward x coordinates of the third distal phalanx.
·**Right and left hand speeds**	The right and left hands speed in the x direction during the underwater trajectory (catch until the exit of the hands from the water).
·**Right and left foot amplitudes**	The maximal difference in the vertical coordinate of the foot between the most up and down positions of the lower limbs actions.
·**Right and left foot speeds**	The right and left foot vertical speed during the downbeats (from the highest vertical position of the feet trajectory until its lowest vertical position), and the upbeats (from the final of the downbeat until the highest vertical position from the feet trajectory).
·**Trunk obliquity**	The angle with the x axis of the segment between the acromion and prominence of the great femoral trochanter.
·**Right and left elbow angle at the pull and push phases**	The difference between the elbow angle at the mid-swim cycle position and beginning of finger backward movement, and end of backward movement and mid-swim cycle position, respectively.
Inter-limb coordination:	
· **Index of Coordination**	Calculated by measuring the lag time between the propulsive phases of each upper limb and expressed as the percentage of the overall duration of the swimming cycle (Chollet et al., 2000). The upper limb propulsive phase begins with the start of the hands backward movement and ends when it exits from the water (pull and push phases), and the non-propulsive phase starts when the hand releases from the water and ends at the beginning of the propulsive phase (recovery and entry phases).Three coordination modes were defined: (i) catch-up, when a lag time occurs between the propulsive phase of the two upper limbs (IdC < 0%); (ii) opposition, when the propulsive phase of one upper limb starts when the other upper limb ends its propulsive phase (IdC = 0); and (iii) superposition when the propulsive phases of both upper limbs are overlapped (IdC > 0%).

Statistical analysis

The normality of the distribution was checked for all variables using Shapiro-Wilk test before comparative analysis. As the conditions of normal distribution or uniformity of variance were not met, non-parametric tests were used. Values were presented as a median and interquartile range (Q1-Q3), which are rather suitable values of central tendency and dispersion for non-parametric data. Friedman test was used to analyse the differences inter-step of the incremental protocol and pairwise multiple *post hoc* comparisons were conducted with Nemenyi's corrections. Wilcoxon signed-rank was used to analyse the differences intra-step (25 vs 175 m) of each step intensity. All statistical procedures were conducted with IBM® SPSS® Statistics system 20 and a P-value ≤ 0.05 was accepted. Effect size (d) for each variable was calculated in accordance with Cohen's (1988), considering a small effect size if $0 \leq |d| \leq 0.2$; (ii) medium effect size if $0.2 \leq |d| \leq 0.5$; and (iii) large effect size if $|d| > 0.5$.

Results

Table 2 presents the median and respective interquartile range (Q1-Q3) values of the general swimming kinematics, IVV, propelling efficiency, segmental kinematics and inter-limb coordination parameters for inter-step incremental swimming comparisons. It was observed an increase in speed and SF, and a decrease in SL, from the 1st to the 7th 200 m step (all for a $P \leq 0.05$; $d \geq 0.53$), with IVV and propelling efficiency remaining stable with the rise of intensity (all for a $P > 0.05$; $d \leq 0.2$). Regarding segmental kinematics, swimmers increased hands backward displacement, and speed and feet vertical speed during upbeat and downbeat actions (all for a $P \leq 0.05$; $d \geq 0.66$), along the protocol, but hip and feet vertical amplitude, trunk obliquity and elbow angle during pull and push phases remained similar despite the swimming intensity increase (all for a $P > 0.05$; $d \leq 0.09$). Furthermore, was observed an increase of the IdC from the first to the last protocol step ($P \leq 0.05$; $d \geq 0.61$), but always selecting the catch-up coordination mode. It is also relevant to highlight that the [La^-] median and interquartile range (Q1-Q3) values observed on the different steps of the incremental protocol were (respectively from the 1st to the 7th step): 1.3 (1.0-1.6), 1.4 (1.0-1.8), 1.8 (1.0-2.4), 2.6 (2.0-3.2), 4.5 (3.5-5.5), 6.6 (5.1-7.2) and 8.2 (7.3-9.1) mmol^{-1}, with all individual AnT values occurring at (or closer to) the 4th 200 m step.

Table 3 depicts the *P* and effect size (*d*) values when comparing intra-step general swimming kinematics, IVV, propelling efficiency, segmental kinematics and IdC parameters. It was observed higher SF and lower SL in the 175 m vs. the 25 m laps for the 5th, 6th and 7th 200 m steps, i.e., at swimming intensities above individual AnT. Nevertheless, IVV and propelling efficiency remained similar within each 200 m steps, independently of the swimming intensity domain. Regarding segmental kinematics, hand backward displacement and speed, as well as feet vertical speed during upbeat and downbeat actions, decreased in the 175 m lap comparing to the 25 m lap at the heavy (5th and 6th steps) and severe (7th step) intensity domains, with a stability in hip and feet vertical amplitude, trunk obliquity and elbow angle during pull and push phases. The IdC values maintained stable between the beginning and final of each 200 m steps until AnT was reached (4th step), but after this point (from the 5th to the 7th steps) it was depicted a notable intra-step increase in the inter-limb coordination values.

Table 2. Median and respective interquartile range (Q1-Q3) of general swimming kinematics, intracyclic velocity variations, efficiency, segmental kinematics and inter-limb coordination for each 200 m step of the incremental protocol.

Step #	1		2		3		4		5		6		7	
Lap #	25 m	175 m	25 m	175 m	25 m	175 m	25 m	175 m	25 m	175 m	25 m	175 m	25 m	175 m
v ($m.s^{-1}$)	$1.13^{b,c,d,f,g}$ (1.10-1.18)		$1.17^{c,d,e,f,g}$ (1.14-1.20)		$1.23^{d,e,f,g}$ (1.20-1.26)		$1.27^{c,f,g}$ (1.24-1.30)		$1.32^{f,g}$ (1.29-1.35)		1.36^{g} (1.32-1.40)		1.43 (1.40-1.46)	
SF (Hz)	$0.45^{b,c,d,e,f,g}$ (0.43-0.50)	$0.46^{b,c,d,e,f,g}$ (0.42-0.48)	$0.47^{d,e,f,g}$ (0.45-0.51)	$0.48^{c,d,e,f,g}$ (0.43-0.50)	$0.51^{d,e,f, g}$ (0.49-0.54)	$0.51^{d,e,f,g}$ (0.49-0.54)	$0.53^{e,f,g}$ (0.52-0.62)	$0.53^{e,f,g}$ (0.51-0.56)	$0.57^{f,g}$ (0.56-0.68)	$0.60^{f,g}$ (0.54-0.62)	0.60^{g} (0.58-0.64)	0.63^{g} (0.59-0.67)	0.67 (0.63-0.77)	0.70 (0.64-0.73)
SL (m)	$2.46^{b,c,d,f,g}$ (2.29-2.58)	$2.45^{b,c,de,f,g}$ (2.29-2.57)	$2.44^{c,d,e,f,g}$ (2.28-2.55)	$2.42^{d,e,f,g}$ (2.31-2.56)	$2.41^{d,e,f,g}$ (2.30-2.53)	$2.39^{d,e,f,g}$ (2.31-2.54)	$2.39^{f,g}$ (2.22-2.50)	$2.37^{e,f,g}$ (2.22-2.48)	$2.31^{f,g}$ (2.22-2.46)	$2.20^{f,g}$ (2.14-2.32)	2.26^{g} (2.18-2.40)	2.15^{g} (2.06-2.29)	2.12 (2.03-2.28)	2.04 (1.89-2.14)
$IVVx_{(CG)}$	0.20 (0.13-0.24)	0.20 (0.15-0.28)	0.21 (0.15-0.25)	0.16 (0.14-0.26)	0.19 (0.12-0.26)	0.19 (0.11-0.22)	0.21 (0.15-0.26)	0.20 (0.16-0.23)	0.24 (0.14-0.29)	0.16 (0.15-0.26)	0.13 (0.10-0.17)	0.13 (0.10-0.23)	0.19 (0.12-0.23)	0.18 (0.14-0.25)
$IVVy_{(CG)}$	0.73 (0.66-0.80)	0.74 (0.66-0.81)	0.72 (0.66-0.75)	0.72 (0.64-0.81)	0.70 (0.64-0.79)	0.75 (0.62-0.83)	0.73 (0.70-0.80)	0.73 (0.68-0.78)	0.77 (0.71-0.82)	0.75 (0.67-0.83)	0.69 (0.65-0.73)	0.72 (0.61-0.77)	0.71 (0.66-0.86)	0.73 (0.68-0.81)
np	0.38 (0.36-0.40)	0.39 (0.36-0.41)	0.38 (0.36-0.41)	0.39 (0.36-0.39)	0.39 (0.36-0.42)	0.37 (0.36-0.39)	0.38 (0.35-0.39)	0.57 (0.34-0.39)	0.35 (0.33-0.38)	0.37 (0.35-0.38)	0.36 (0.34-0.38)	0.36 (0.34-0.37)	0.35 (0.32-0.40)	0.35 (0.31-0.38)
RHa (m)	0.20 (0.18-0.25)	0.22 (0.19-0.24)	0.20 (0.17-0.23)	0.21 (0.19-0.25)	0.20 (0.17-0.23)	0.20 (0.18-0.23)	0.19 (0.15-0.22)	0.21 (0.17-0.24)	0.19 (0.17-0.20)	0.20 (0.18-0.22)	0.19 (0.16-0.21)	0.20 (0.17-0.22)	0.18 (0.14-0.22)	0.19 (0.16-0.24)
LHa (m)	0.23 (0.21-0.25)	0.23 (0.21-0.27)	0.23 (0.20-0.25)	0.24 (0.22-0.26)	0.21 (0.20-0.23)	0.23 (0.20-0.24)	0.21 (0.18-0.24)	0.22 (0.21-0.26)	0.20 (0.19-0.22)	0.22 (0.20-0.23)	0.21 (0.19-0.23)	0.22 (0.20-0.23)	0.20 (0.18-0.23)	0.21 (0.18-0.23)
BD	$1.02^{b,c,d,e,f,g}$ (0.81-1.12)	$1.01^{b,c,d,e,f,g}$ (0.80-1.15)	$0.99^{c,d,e,f,g}$ (0.81-1.11)	$0.97^{c,d,e,f,g}$ (0.66-1.09)	$0.95^{d,e,e,f,g}$ (0.70-1.19)	$0.93^{d,e,f,g}$ (0.66-1.11)	$0.92^{e,f,g}$ (0.70-1.19)	$0.90^{e,f,g}$ (0.61-1.18)	$0.88^{f,g}$ (0.72-1.22)	$0.73^{f,g}$ (0.59-1.09)	0.80^{g} (0.59-1.06)	0.64^{g} (0.59-0.90)	0.64 (0.58-0.95)	0.62 (0.57-0.97)
$v_{(rhand)}$ ($m.s^{-1}$)	$2.28^{b,d,d,e,f,g}$ (2.10-2.54)	$2.26^{b,c,d,fg}$ (2.04-2.40)	$2.31^{c,d,e,f,g}$ (2.09-2.54)	$2.29^{c,d,f,f}$ (2.00-2.58)	$2.36^{d,e,f,g}$ (2.19-2.63)	$2.34^{d,e,f,g}$ (2.13-2.56)	$2.40^{e,f,g}$ (2.14-2.54)	$2.38^{,e,f,g}$ (2.16-2.55)	$2.42^{f,g}$ (2.31-2.65)	$2.40^{f,g}$ (2.17-2.62)	2.49^{g} (2.29-2.78)	2.46^{g} (2.19-2.62)	2.53 (2.35-2.79)	2.50 (2.28-2.73)
$v_{(lhand)}$ ($m.s^{-1}$)	$2.20^{b,c,d,e,f,g}$ (2.10-2.39)	$2.18^{b,c,d,e,f}$ (2.03-2.31)	$2.24^{c,d,e,f,g}$ (2.10-2.49)	$2.23^{c,d,e,f}$ (2.03-2.41)	$2.35^{d,e,f,g}$ (2.21-2.72)	$2.36^{d,e,f,g}$ (2.12-2.60)	$2.37^{e,f,g}$ (2.22-2.52)	$2.39^{e,f,,g}$ (2.36-2.54)	$2.41^{f,g}$ (2.31-2.65)	$2.42^{f,g}$ (2.17-2.52)	2.50^{g} (2.23-2.52)	2.48^{g} (2.24-2.57)	2.55 (2.34-2.73)	2.53 (2.27-2.72)
RFa (m)	0.45 (0.41-0.48)	0.44 (0.34-0.48)	0.44 (0.34-0.49)	0.41 (0.33-0.46)	0.42 (0.34-0.47)	0.43 (0.33-0.49)	0.45 (0.37-0.50)	0.43 (0.39-0.51)	0.42 (0.39-0.51)	0.47 (0.33-0.51)	0.42 (0.35-0.57)	0.44 (0.41-0.51)	0.49 (0.42-0.63)	0.49 (0.42-0.63)
LFa (m)	0.46 (0.37-0.52)	0.48 (0.37-0.59)	0.44 (0.34-0.49)	0.41 (0.33-0.46)	0.42 (0.34-0.47)	0.43 (0.33-0.49)	0.45 (0.37-0.50)	0.43 (0.39-0.51)	0.45 (0.40-0.51)	0.47 (0.33-0.51)	0.43 (0.38-0.48)	0.44 (0.34-0.51)	0.50 (0.43-0.59)	0.48 (0.39-0.59)

RFv (m.s^{-1}) downbeat	-1.0^{b,c,de,f,g} (-1.8- -0.2)	-1.0 ^{b,c,de,f,g} (-1.8- -0.4)	-1.2 ^{c,d,e,f,g} (-2.0- -0.4)	-1.2^{c,d,e,f,g} (-1.6- -0.6)	-1.4^{d,e,f,g} (-1.8- -0.4)	-1.3 ^{d,e,f,g} (-1.8- -0.2)	-1.6^{e,f,g} (-1.8- -0.6)	-1.5 ^{e,f,g} (-1.8- -0.4)	-2.0^{f,g} (-2.2- -0.4)	-1.7 ^{,f,g} (-2.0- -0.6)	-2.24^{g} (-2.4- -0.8)	-1.9^{g} (-2.4- -0.6)	-2.28 (-2.45- -0.9)	-2.13 (-2.38- -0.9)
LFv (m.s^{-1}) downbeat	-1.0^{b,ce,f,g} (-1.7- -0.2)	-1.0 ^{b,c,de,f,g} (-1.7- -0.5)	-1.2 ^{c,d,e,f,g} (-1.8- -0.2)	-1.1 ^{c,d,e,f,g} (-1.7- -0.3)	-1.4$^{d, e,f,g}$ (-1.7- -0.4)	-1.3 $^{d, e,f,g}$ (-1.6- -0.4)	1.6 ^{e,f,g} (-1.5- -0.6)	-1.6 ^{e,f,g} (-1.7- -0.4)	-2.1 ^{f,g} (-2.2 -0.8)	-1.7^{f,g} (-2.0- -0.5)	-2.26 ^{g} (-2.4- -0.7)	-2.0^{g} (-2.2- -0.7)	-2.28 (-2.40- -0.9)	-2.10 (-2.35- -0.9)
RFv (m.s^{-1}) upbeat	0.5^{b,c,d,e,f,g} (0.2-1.0)	0.4 ^{b,c,de,f,g} (0.2-0.9)	0.7 ^{c,d,e,f,g} (0.2-1.2)	0.6 ^{c,d,e,f,g} (0.2-1.1)	0.9 $^{d, e,f,g}$ (0.3-1.2)	0.8 $^{d, e,f,g}$ (0.2-1.0)	1.1^{e,f,g} (0.3-1.2)	1.1 ^{e,f,g} (0.3-1.2)	1.6 ^{f,g} (0.4-1.9)	1.3 ^{f,g} (0.4-1.8)	1.8 ^{g} (0.6-2.1)	1.5 ^{g} (0.6-1.9)	2.0 (0.8-2.2)	1.7 (0.6-2.1)
LFv (m.s^{-1}) upbeat	0.5^{b,ce,f,g} (0.2-1.0)	0.4 ^{b,c,de,f,g} (0.2-0.9)	0.8 ^{c,d,e,f,g} (0.2-1.2)	0.6 ^{c,d,e,f,g} (0.2-1.1)	1.0 $^{d, e,f,g}$ (0.3-1.4)	0.9 $^{d, e,f,g}$ (0.2-1.3)	1.2 ^{e,f,g} (0.3-1.4)	1.1 ^{e,f,g} (0.3-1.4)	1.7 ^{f,g} (0.4-1.9)	1.4 ^{f,g} (0.4-1.9)	1.9 ^{g} (0.6-2.1)	1.6 ^{g} (0.6-2.0)	2.11 (0.8-2.2)	1.8 (0.6-2.2)
TI (º)	7.23 (6.11-8.15)	7.31 (6.21-8.11)	7.51 (6.04-8.20)	7.03 (5.98-8.12)	7.14 (6.04-8.21)	6.41 (5.14-7.34)	7.12 (6.36-8.10)	6.20 (5.10-7.43)	6.98 (5.11-7.34)	6.21 (5.43-6.57)	6.78 (5.21-7.71)	6.10 (5.08-6.81)	6.34 (5.78-7.26)	6.98 (5.11-7.38)
REA (º) pull	46.13 (40.1-52.1)	46.33 (39.1-43.1)	45.16 (39.1-51.2)	44.06 (40.2-49.3)	44.21 (41.2-47.7)	46.53 (41.1-50.6)	44.17 (42.2-52.4)	46.23 (40.1-53.1)	45.11 (40.8-52.1)	46.25 (38.1-53.3)	47.37 (39.2-54.1)	46.41 (40.2-53.1)	45.19 (39.1-52.4)	47.49 (36.13-55.06)
LEA (º) pull	44.07 (41.1-46.3)	45.36 (39.1-47.5)	46.16 (40.3-50.2)	44.08 (38.1-49.1)	47.17 (42.7-52.1)	45.21 (43.1-50.2)	44.30 (42.2-50.1)	45.68 (39.2-47.8)	46.14 (39.6-50.1)	44.24 (43.3-45.7)	44.64 (42.1-48.1)	47.15 (36.6-55.1)	47.38 (42.16-52.23)	45.19 (43.6-50.3)
REA (º) push	33.12 (29.1-36.2)	35.29 (30.1-39.6)	36.14 (23.3-39.1)	35.11 (25.3-45.5)	33.18 (23.1-43.1)	35.29 (30.2-39.3)	33.24 (23.1-43.1)	35.36 (30.1-39.2)	34.84 (24.1-43.6)	36.14 (26.2-43.3)	33.54 (23.1-43.3)	34.68 (24.3-43.7)	36.82 (29.2-39.27)	35.64 (28.6-40.2)
LEA (º) push	34.25 (29.2-38.6)	35.33 (27.3-42.5)	34.27 (28.2 -36.1)	35.11 (28.3-40.6)	33.21 (25.1-41.3)	36.41 (28.2-40.8)	34.24 (30.3-38.4)	36.15 (28.1-41.4)	34.34 (26.1-41.2)	35.43 (25.7-45.2)	34.58 (30.6-39.7)	35.32 (30.1-38.1)	34.21 (30.4-39.7)	33.18 (23.7-42.8)
IdC	-19^{b,c,d,e,f,g} (-21- - 15)	-18^{b,c,d,e,f,g} (-20 - -16)	-17^{c,d,e,f,g} (-19 - -15)	-16^{c,d,e,f,g} (-19 - -17)	-15^{d,e,f,g} (-18 - -13)	-14^{d,e,f,g} (-18 - -13)	-13^{e,f,g} (-17 - -12)	-12^{e,f,g} (-16 - -11)	-10^{f,g} (-12 - -8)	-8^{f,g} (-10 - -6)	-8^{g} (-10- -6)	-6^{g} (-8 - -5)	-5 (-7 - -3)	-3 (-5 - -2)

Note: speed (v), stroke frequency (SF), stroke length (SL), horizontal intracyclic velocity variations ($IVVx_{CG}$), vertical intracyclic velocity variations ($IVVy_{CG}$), propelling efficiency (np), right hip vertical amplitude (RHa), left hip vertical amplitude (LHa), horizontal hands backward displacement (BD), horizontl right hand speed (v_{rhand}), horizontal left hand speed (v_{lhand}), right foot amplitude (RFa), left foot amplitude (LFa),vertical right foot speed during upbeats and dowbeats (RFv), vertical left foot speed during upbeats and downbeats (LFv), trunk obliquity (TI), right elbow angle at the pull and push phases (REA), left elbow angle at pull and push phases (LEA) and index of coordination (IdC). $^{b, c, d, e, f, g}$ Different from 2nd, 3rd,4th, 5th, 6th and 7th steps, respectively ($P \leq 0.05$).

Table 3. Comparison between the first (25 m) and the penultimate (175 m) lap of each 200 m step of the incremental protocol for general swimming kinematics, intracyclic velocity variations, segmental kinematics and inter-limb coordination. *P*-values and effect size (*d*) obtained from the Wilcoxon signed-rank test are reported.

Step ≠	1		2		3		4		5		6		7	
Lap ≠	25 m vs 175 m		25 m vs 175 m		25 m vs 175 m		25 m vs 175 m		25 m vs 175 m		25m vs 175m		25 m vs 175 m	
	P	*d*	*P*	*d*	*P*	*d*	*P*	*d*	*P*	*d*	*P*	*d*	*P*	*d*
SF (Hz)	0.72	0.04	0.50	0.04	0.72	0.03	0.05	0.39	0.00*	0.66	0.00*	0.61	0.02*	0.68
SL (m)	0.79	0.03	0.95	0.02	0.56	0.07	0.06	0.31	0.03*	0.61	0.00*	0.64	0.02*	0.63
$IVVx_{(CG)}$	0.11	0.18	0.93	0.06	0.28	0.16	0.24	0.14	0.38	0.17	0.50	0.14	0.38	0.08
$IVVy_{(CG)}$	0.50	0.06	0.95	0.03	0.64	0.09	0.33	0.12	0.83	0.04	0.57	0.13	0.87	0.04
np	0.33	0.03	0.57	0.07	0.16	0.06	0.09	0.11	0.07	0.19	0.95	0.06	0.11	0.12
RHa (m)	0.44	0.04	0.07	0.28	0.59	0.16	0.06	0.21	0.08	0.18	0.07	0.16	0.79	0.09
LHa (m)	0.13	0.18	0.08	0.15	0.59	0.15	0.11	0.32	0.44	0.13	0.64	0.13	0.79	0.08
BD (m)	0.09	0.17	0.09	0.23	0.14	0.25	0.16	0.23	0.04*	0.52	0.02*	0.54	0.03*	0.57
$v_{(rhand)}$ ($m.s^{-1}$)	0.13	0.21	0.16	0.22	0.13	0.15	0.33	0.02	0.01*	0.64	0.03*	0.59	0.04*	0.54
$v_{(lhand)}$ ($m.s^{-1}$)	0.38	0.26	0.38	0.24	0.10	0.13	0.64	0.03	0.01*	0.63	0.04*	0.57	0.02*	0.60
RFa (m)	0.24	0.17	0.38	0.09	0.76	0.04	0.79	0.05	0.79	0.08	0.10	0.21	0.33	0.08
LFa (m)	0.06	0.26	0.38	0.04	0.76	0.04	0.79	0.08	0.87	0.07	0.38	0.07	0.18	0.09
RFv ($m.s^{-1}$) downbeat	0.17	0.16	0.12	0.22	0.15	0.25	0.31	0.10	0.02*	0.59	0.01*	0.69	0.01*	0.64
LFv ($m.s^{-1}$) downbeat	0.28	0.18	0.39	0.14	0.12	0.13	0.41	0.13	0.03*	0.53	0.01*	0.63	0.01*	0.61
RFv ($m.s^{-1}$) upbeat	0.69	0.13	0.85	0.11	0.26	0.17	0.10	0.31	0.03*	0.58	0.01*	0.61	0.01*	0.63
LFv ($m.s^{-1}$) upbeat	0.18	0.16	0.17	0.12	0.18	0.19	0.15	0.29	0.04*	0.60	0.00*	0.72	0.00*	0.65
TI (º)	0.08	0.16	0.28	0.08	0.46	0.08	0.69	0.09	0.67	0.08	0.48	0.08	0.38	0.11
REA (º) pull	0.22	0.27	0.28	0.10	0.86	0.05	0.69	0.09	0.79	0.09	0.16	0.18	0.53	0.07
LEA (º) pull	0.35	0.06	0.67	0.08	0.26	0.05	0.10	0.16	0.09	0.11	0.13	0.09	0.13	0.17
REA (º) push	0.51	0.09	0.87	0.07	0.64	0.10	0.37	0.13	0.87	0.08	0.53	0.17	0.97	0.08
LEA (º) push	0.18	0.11	0.82	0.05	0.58	0.09	0.22	0.09	0.28	0.1	0.47	0.11	0.48	0.07
IdC	0.16	0.18	0.33	0.09	0.14	0.19	0.21	0.12	0.02*	0.56	0.03*	0.51	0.04*	0.51

Note: stroke frequency (SF), stroke length (SL), horizontal intracyclic velocity variations of the centre of mass ($IVVx_{CG}$), vertical intracyclic velocity variations of the centre of mass ($IVVy_{CG}$), propelling efficiency (np), right hip vertical amplitude (RHa), left hip vertical amplitude (LHa), horizontal hands backward displacement (BD), horizontal right hand speed (v_{rhand}), horizontal left hand speed (v_{lhand}), right foot amplitude (RFa), left foot amplitude (LFa), vertical right foot speed during upbeats and downbeats (RFv), vertical left foot speed during upbeats and downbeats (LFv), trunk obliquity (TI), right elbow angle at the pull and push phases (REA), left elbow ngle at the pull and push phases (LEA) and index of coordination (IdC). * Difference between the 25 m and the 175 m lap ($P \leq 0.05$).

Discussion

As swimming training aims achieving proper biophysical adaptations, swimmers technique need to be adapted to comply with environmental and task demands imposed by different exercise intensities (Komar et al., 2012). Such adaptations should be rigorously controlled through 3D kinematics, which provides an in-depth motion analysis. The current study offers original inter and intra-steps 3D kinematical data along front crawl performed from low to severe intensities. Main findings indicate that swimmers changed their general swimming parameters, segmental kinematics and inter-limb coordination when increasing inter-step speed and also within each 200 m steps but only for intensities after the point at which AnT was reached. Concomitantly with these changes, IVV and propelling efficiency stayed stable independently of the swimming intensities, suggesting that swimmers adapt their technique to satisfy swimming speed increments.

The relationship among speed, SF and SL in each competitive swimming event is a major point of interest in applied biomechanics (Barbosa et al., 2010). In the current study, the inter-steps speed and SF increase, and SL decrease, corroborate previous 2D data (Barbosa et al., 2015; Fernandes et al., 2011; Psycharakis et al., 2008; Figueiredo et al., 2013a) and are explained by the technique reorganization to overcome increased hydrodynamic drag (Komar et al., 2012; Seifert et al., 2014). Regarding the intra-step analysis, our findings evidence that the AnT, more than a physiological threshold, is a biomechanical boundary (Dekerle et al., 2005; Figueiredo et al., 2013a; Oliveira et al., 2012), and that when performing above this point swimmers are not any more in homeostatic conditions (Peinado e al., 2014). In fact, swimmers kept a low SF and a high SL within the steps performed at low and moderate intensities (where the aerobic system covers almost all the energy demands), in opposition to the SF increase and SL decrease at high speeds profile (at heavy and severe intensities, revealing an augmented anaerobic contribution and an increased activity in type II or fast twitch muscle fibers) (Figueiredo et al., 2013a; Peinado et al., 2014).

Complementarily, IVV assessment is considered as quite important to better understand performance evolution constraints (Figueiredo et al., 2012a; Psycharakis et al., 2010; Vilas-Boas et al., 2010). In the current study, the observed inter and intra-steps IVV stability, independently of the swimming intensity domain, is in accordance with the literature (Barbosa et al., 2015; Figueiredo et al., 2013b) and is justified by the adaptation of upper and lower limbs actions to overcome hydrodynamic drag at higher speeds (Seifert et al., 2010). In fact, it was suggested that swimmers need to maintain low IVV values by using upper and lower limbs continuous actions to minimize their energy cost when performing at high speeds (for a detailed analysis on the notable relationship between energy expenditure and IVV in incremental exercise cf. Vilas-Boas et al., 2010). As propelling efficiency has depicted a similar inter and intra-steps profile, it means that our swimmers were economical when performing the intensity increments (as suggested before using 300 m step lengths; Komar et al., 2012), evidencing that its maintenance (or increase) would bring about a decrease in energy cost and vice versa (Zamparo et al., 2005). The maintenance in propelling efficiency (Komar et al., 2012), IdC (Alberty et al., 2009) and IVV (Seifert et al., 2010) within a specific effort could be due to SF and SL adaptations through upper and lower limb actions.

Considering specifically the upper limbs actions, we have noticed a reduction in horizontal hand displacement and an increase in horizontal hand speed when going from low to severe intensities, indicating a glide reduction during the entry phase and greater focus on propulsive force application during the pull and push phases (Seifert et al., 2007). Conversely, hand related parameters were stable intra-laps at steps below the AnT and, from 5^{th} to 7^{th} speed increment, a decrease in horizontal hand displacement and speed was found. These results show that swimmers when performing at low and moderate intensities adopted a more lateral-medial trajectory to obtain a more lift force based propulsion (Gourgoulis et al., 2014a) and that at intensities higher than the AnT, when a metabolic imbalance of muscle ability occurs for lactate oxidation (Figueiredo et al., 2013a), swimmers decreased hand force production within the 200 m steps (Fernandes et al., 2011). In addition, the decrease in horizontal hand displacement and speed were not influenced by elbow angle and trunk rotation, in opposition with previous findings on a 200 m maximal effort (Figueiredo et al., 2012b). In fact, as our swimmers presented an elbow angle and trunk obliquity stabilization during pull and push phases (both within each step and along the incremental protocol), it is suggested that they were able to maintain an optimal combination of elbow flexion-extension and transverse shoulder adduction as the trunk rolled back towards the neutral position (Payton et al., 2002; Sanders et al., 2009).

It is known that front crawl lower limb actions also contributes to overall propulsion (Gourgoulis et al., 2014b), enabling 10% speed increments (Deschodt et al., 1999). In the current study, when intensity increased up to the severe domain (last 200 m step), vertical feet speed during upbeat and downbeat actions increased, indicating a considerable lower limb contribution at speeds between 1.00 and 1.50 $m.s^{-1}$ (as previously observed; Gatta et al., 2012). However, a reduction in vertical feet speed in-between the 25 and 175 m laps over the 4th 200 m step was observed, which can be explained by a fatigue effect (Figueiredo et al., 2012a). Despite this appearance of fatigue at intensities higher than the AnT, hip and feet vertical amplitude were not affected (for both inter and intra step comparisons), probably due to the maintenance of coordinated coupling actions between up and downbeats (Gatta et al., 2012; Gourgoulis et al., 2014a). In fact, it was previously noticed that this lower limb actions strategy would lead to a more horizontal body position (Figueiredo et al., 2012b), to a reduced frontal hydrodynamic drag (Zamparo et al., 2005), improving overall propulsion and inter-limb coordination (Figueiredo et al., 2013b).

Lastly, it was observed that swimmers, although maintaining a catch-up coordination mode, increased their IdC along the step intensity increments, as well as in-between the 25 to 175 m laps at the 5-7th 200 m steps. We were expecting some qualitative changes in the coordination mode when swimming from low to severe intensities since there is a trend for a shift from catch-up to opposition and superposition mode as speed increases (Seifert et al., 2007). However, our swimmers achieved a maximal mean speed and SF of 1.43 $m.s^{-1}$ and ~0.70 Hz (respectively), which seems not to be enough to imply an adaptation to an opposition coordination mode (corroborating literature in incremental protocols; Komar et al., 2012). It is true that it was observed before both catch up and opposition coordination modes at the final lap of a maximal event (Alberty et al., 2009; Figueiredo et al., 2013b), indicating that different inter-arm coordination profiles are dependent of swimming intensity domain, swimmers competitive level and, also, in the methodological procedures used for assessing IdC.

Study limitations

Notwithstanding the originality and relevance of the current data, some limitations should be presented. In fact, although a ten swimmers sample is common in swimming related studies that require subjects availability for familiarization and complex data collection methodology testing protocols (Figueiredo et al., 2011; Puel et al., 2012), it is recognized that a larger sample size might be more representative of the population, limiting the influence of outliers or extreme observations. Therefore, future studies should verify if a larger sample could evidence a better picture for the 3D analysis during incremental protocols. In addition, the two swimming cycles digitized per lap are paramount to be highlighted since most of the 3D kinematic studies have analysed a unique swimming cycle. However, as kinematic analysis has evolved with opto-electronic tools, forthcoming studies should consider including more swimming cycles from each lap at different swimming intensities.

Conclusion

Changes in general swimming and segmental kinematics, and inter-limb coordination values occurred through low to severe front crawl intensities and within laps (when performing above the AnT). Complementarily, IVV and propelling efficiency remained stable independently of intensity changes. Therefore, by analyzing thoroughly the inter and intra-step behaviour of key biomechanical parameters in an incremental protocol, it is possible to observe detailed swimmers strategy useful for better understand training adaptations at different training and competing speeds. Further experiments on the topic are encouraged, particularly to characterize the underlying mechanism regarding 3D kinematic behaviour in different performing groups (conducting similar training series) and also in other swimming techniques.

Pratical Applications

As accurate and reliable biomechanical analysis provides relevant data for successful development of swimming performance, coaches should include a 3D kinematical characterization per macrocycle in each competitive season. A close look at the heavy and severe swimming intensities are recommended once the increase in load after reaching the AnT leads the organism to start facing homeostatic difficulties that imply a reorganization in swimming technique.

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Chapter 7 General Discussion

Training control and evaluation is often used as part of an elite training program to objectively assess the likely outcome of a swimming competitive performance (Anderson et al., 2008). Thus, researchers and coaches have often implemented sets of tasks (like the step incremental protocol) that allow quantifying the development of swimmers' performance determinant factors, as well as the result and adequacy of training exercises programs (Fernandes et al., 2009). The step incremental protocol allows the assessment of several key physiological features, which are useful for diagnosis and training in competitive swimming (e.g. aerobic potential; Reis et al., 2012). Complementarily, the biomechanical assessment helps coaches to improve understanding about technique adaptations in a wide-range of training intensities (Barbosa et al., 2010; Komar et al., 2012; Psycharakis et al., 2008). The general purpose of this Thesis was to select the most proper variant of a front crawl intermittent incremental protocol and deeply characterize it across low to severe intensities using updated physiological and biomechanical methods.

Our main findings were: (i) VO_2 time averaging intervals studied at three different intermittent incremental protocol variants revealed that shorter intervals (i.e. from 5 to 15 s) should be used at 200 and 300 m step variants for VO_2max assessment, once accounted for higher percentage of VO_2 plateau incidence and higher VO_2max values compared with 400 m step variant; (ii) general swimming, segmental and anatomical landmark kinematics, horizontal and vertical intracyclic velocity variations, propelling efficiency and inter-limb coordination did not alter throughout 200, 300 and 400 m incremental protocol variants; (iii) based on physiological and biomechanical findings, and practical and logistical reasons, 200 m incremental protocol variant was recommended as the most appropriated to assess swimmers' physiological and kinematical parameters; (iv) 5 to 15 s VO_2 time-averaging intervals were the most accurate and reliable to characterize VO_2 kinetics from low to severe intensities during 200 m incremental protocol; (v) during 200 m front crawl performed at extreme intensity, 5 to 15 s intervals were also the most appropriated to assess VO_2peak and VO_2max values; (vi) VO_2 kinetics pattern during 200 m step length variant remained stable within low-moderate intensity, but across heavy and severe intensities it was noticed faster VO_2 kinetics, shorter time constant and time delay values and greater VO_2 gains in the primary component (with a noticeable slow component); (vii) the new calibration frame provided low and accurate 3D RMS reconstruction errors to assess detailed swimmers' kinematics; (viii) the 3D kinematic assessment during the 200 m incremental protocol variant revealued that swimmers changed general swimming and segmental kinematics, and inter-limb coordination from low to severe intensities, as well as within 200 m increments after AnT, although maintained intracyclic speed fluctuation and propelling efficiency across all intensities and within the seven 200 m increments.

Swimming has become a very competitive sport, since races have been won or lost by tenths of a second, with training process effectiveness requiring rigorous monitoring on regular basis (Jürimäe et al., 2007; Smith et al., 2002). Thus, coaches and their collaborators often implement a set of tasks to control and evaluate swimmer's performance, allowing proper training sets design (Fernandes et al., 2011). The step incremental protocol is used to define crucial training intensities (e.g. vVO_2max) throughout n x 200 m step variant (Costill et al., 1992; Pyne et al., 2001) and has been under scientific community spotlights since 1990 s. However, the necessity of using longer step durations to allow sufficient time to blood [La^-] better express the muscular lactate production has been questioned (e.g. Kuipers et al., 2003). The study conducted in **Appendix I** revealed that, with a proper time-averaging interval (i.e. ≤ 15 s), 200 and 300 m intermittent incremental protocol variants depicted higher VO_2 plateau incidence at VO_2max than the 400 m variant, partially corroborating our previous established hypothesis. The primary criterion for evaluating the quality of an incremental protocol is the occurrence of a VO_2max plateau (Astorino et al., 2000; Midgley et al., 2007; Sánchez-Otero et al., 2014) and previous studies had already reported that it can be properly assessed using short time-averaging intervlas (Astorino, 2000; Midgley et al., 2008; Myers et al., 1990). From an energetic point of view, this finding allows suggesting that 200 m incremental protocol variant is the most suitable to be used, as it would decrease the time needed to individually assess swimmers aerobic potential, with no significant impact on data accuracy. Coaches who opt to use 400 m variant should be supported by secondary objective criteria (R, HR_{max} and La^{-}_{max}) that can increase the likelihood of achiving the real VO_2max.

Since technical changes monitoring can improve physiological behaviour understanding at different training intensities (Komar et al., 2012), **Chapter 2** and **Appendix II** explained through kinematics how swimmers overcome environmental constraints imposed by the three intermittent incremental protocol variants. As front crawl technique is very performed in different intensities during training (Psycharakis et al., 2008), it was expected that swimmers would implement similar kinematic strategies regardless step length, which might result from a preprogrammed coordinative pattern (Eloranta, 1997). Therefore, it is possible to consider that swimmers' past experiences can have a strong influence on movement output, as they seem to select a stereotype strategy similar to that previously used in training (Rodacki & Fowler, 2001). In fact, it was demonstrated that, even if a different strategy is selected, characteristics of a learned movement pattern interfere consistently with critical characteristics of movement, even in skilled performers (Walter & Swimmen, 1994), and a preferred common strategy may arise.

As the 200 m intermittent incremental protocol variant is less disturbing in training schedule, it was conducted an analysis to determine the most proper sampling interval to be used from low to severe intensities (**Chapter 3**), as also done in **Appendix I**. Furthermore, it was analysed the influence that different time averaging intervals have during a supra-maximal exercise (**Appendix III**). The selection of optimal sampling strategies is fundamental to the validation and comparison of research findings, as well as to the correct training diagnosis and intensities prescription (Midgley et al., 2008). Findings revealed that VO_2 values were higher for all swimming efforts when using breath-by-breath and 5 s average than ≥ 10 s, partially agreeing with our hypotheses defined for low-moderate, heavy and severe intensities. As 10 and 15 s averages were those that showed the lowest changes on VO_2 responses, they should be implemented in 200 m incremental protocol variant from low to severe intensities to adequately represent variations in O_2 loading in the lungs or its utilization in the muscles at this wide range of intensities. Previous studies in running (Astorino, 2009; Midgley et al., 2007; Myers et al., 1990) and cycling (Hill et al., 2003) have shown that breath-by-breath and 5 s time-averaging intervals overestimated VO_2 values regardless the selected race pace. Short time-averaging intervals were also not recommended to assess VO_2 at supraximal 200 m intensity, due to the higher possibility of selecting an artefact caused by high ventilation and respiratory frequency (**Appendix III**). Based on **Chapter 3** and **Appendix III** it would be pertinent to examine the best VO_2 time-averaging interval from low to all out 300 and 400 m efforts.

Studies conducted in **Chapter 3** and **Appendix I** allowed determining that short time-averaging intervals would coherently adjust VO_2 magnitude at 200, 300 and 400 m protocol variants. Thus, the 5 s average interval was tested to quantify the VO_2 kinetic parameters at low-moderate, heavy, severe and extreme intensities (**Appendix IV**, **Chapter 4** and **Appendix V**). Firstly we compared amplitudes, time delays and time constants between two common training intensities (i.e. AnT and all-out) and verified a faster VO_2 kinetics at maximal 200 m effort, which corroborates the previous hyphotesis (**Appendix IV**). It can be justified by the higher O_2 demand at all out efforts since intensity and respiratory effort increase (Carter et al., 2000; Pringle et al., 2003). Similarly to above described findings, a faster VO_2 kinetics was observed from AnT to VO_2max using a bi-exponetial function (**Chapter 4**), contrarily the mono-exponential modelling used in **Appendix IV**. Double-exponential function is considered to better describe the VO_2SC, which is a common observed physiological phenomenon when swimming at intensities around VO_2max, as also noticed in **Chapter 4** (Demarie et al., 2001; Sousa et al., 2014). Being 300 m and alternative distance using in incremental protocols, the VO_2 kinetics analysis also revealed the appearance of an increased VO_2SC at the 5th and later steps (**Appendix V**). These findings highlight that VO_2SC has a relevant physiological meaning at swimming intensities above AnT.

To complement **Chapter 4** findings it was examined the swimming kinematic adaptations at those target training velocities, which would enable coaches to develop optimal training drills to overcome environmental (i.e. increase in speed) and task (i.e. swimming on a given distance) constraints imposed by the n x 200 m incremental protocol variant (Figueiredo et al., 2013; Komar et al., 2012; Seifert et al., 2010). Calibration volume is essential to quantify swimming 3D movements in detail, which occurs in a large space, which implied the construction of a novel structure attempting to achieve this goal (**Chapter 5**). Contrarily to what has been described (Kwon & Caselbolt, 2006; Silvatti et al., 2012), large calibration volumes can be used for swimming movement analysis in detail, but considering projective geometry correction methods, as homography. In fact, it was tested the homography estimation method that revealed lower RMS errors than without homography for surface and underwater cameras, confirming our hypothesis. The benefit of homography for 3D reconstruction is well - recognized (Alvarez et al., 2011; Nejadas & Linderbergh, 2014; Zeng et al., 2008) and, such method, has been recommended to improve camera calibration (Alvarez et al., 2011; Zhang et al., 2000) and 3D reconstruction (Wang, 2005).

Following the calibration volume developing that enables at least the assessment of two swimming cycles, **Chapter 6** added to the previous physiological related study (**Chapter 4**) 3D kinematic assessment to complement **Chapter 2** and **Appendix II** findings. It was described and compared swimmers technique adaptions between steps and within laps of each 200 m step of incremental protocol. As expected, swimmers changed general swimming and segmental kinematical parameters and inter-limb coordination from low to severe intensities and within 200 m increments at 5th, 6th and 7th steps. Previous studies reported similar results to those observed in comparisons between steps, which might be explained by a swimmers' technique reorganization to overcome the increased forward resistance provided from speed increments (Komar et al., 2012; Seifert et al., 2014). Kinematical changes within 5th, 6th and 7th steps can be due to a biomechanical boundary from steps corresponding the AnT (e.g. Figueiredo et al., 2013; Costa et al., 2012). In those steps it was previously noticed the appearance of a slow component (**Chapter 4**), which can be related to work capacity impairment and higher oxygen demand (Pringle et al., 2003). Accepting previous statements mentioning that swimmers need to maintain low intracyclic velocity variations through a high continuity of upper and lower limb actions at any intensity (Seifert et al., 2014), intracyclic velocity variation and propelling efficiency showed a stable behaviour despite the physiological changes occurred in the 5th, 6th and 7th steps of the incremental protocol.

Chapter 8 Conclusions

Following the findings obtained in the collection of studies presented in this Thesis, it seems reasonable to stress out the following conclusions:

(i) Methods of proper VO_2 kinetics assessment were used for the first time in swimming, and revealed that time-averaging intervals ≤ 15 s allowed the highest VO_2 plateau incidence regardless the step length, 200, 300 and 400 m;

(ii) Higher percentage of VO_2 plateau incidence and VO_2max were noticed for 200 and 300 rather than 400 m protocol and 10 s time-averaing intervals was suggested as the most suitable for 200 m protocol variant;

(iii) General swimming, segmental and anatomical landmarks, horizontal intracyclic velocity variations, propelling efficiency and inter-limb coordination remained similar across 200, 300 and 400 m protocols variants;

(iv) Based on physiological and biomechanical findings and from a holistic point of view, the 200 m protocol variant seem to be well-rounded and comprehensive way to simultaneously monitor swimmers' energetic, biomechanical and motor-control profiles;

(v) From low to severe intensities using the 200 m intermittent protocol variant, significant alterations on VO_2 values was associated with short time-averaging intervals (≤ 5 s) and low variation was obtained by using ≥ 10 s time-averaging intervals;

(vi) At 200 m performed at extreme intensity, 5 to 15 s intervals were the most appropriated;

(vii) VO_2 kinetics pattern during 200 m protocol variant remained stable within the range of intensities corresponding to low-moderate (up to the AnT boundary); reaching a steady state;

(viii) During heavy and severe intensities of the 200 m protocol variant, fast VO_2 kinetics (short time constant and time delay values) and great VO_2

gains in the primary component were noted, with the appearance of a conspicuous slow component at ~130 s (Δ VO_2 > 250 $ml.min^{-1}$);

(ix) Using homography, RMS errors of control and validation points were smaller than without homography use and remained similar between surface and underwater cameras;

(x) Without homography, RMS errors of control points were greater for underwater rather than for surface cameras and, in opposition, RMS errors of validation points were greater for surface than for underwater cameras;

(xi) Homography transformation on the new calibration frame provided low and accurate 3D RMS reconstruction errors to assess detailed swimmers' kinematic considering two swimming cycles;

(xii) The 3D kinematical analysis during 200 m protocol variant indicated that swimmers changed general swimming parameters, segmental kinematics and inter-limb coordination between low to severe swimming intensities and within 200 m increments performed after 4^{th} 200 m step (i.e. above the AnT);

(xiii) Horizontal and vertical intraclyclic velocity variations and propelling efficiency patterns during 200 m protocol variant remained stable from low to severe intensities.

Chapter 9 Suggestions for Future Research

This Thesis considered methodological improvements to provide swimming coaches with some initial and objective evidence to allow the understanding of physiological and biomechanical aspects of the most recommended intermittent incremental protocol variant. However, some gaps and limitations still remains, being our purpose in examine in other studies, namely:

(i) Development of a system that could allow $[La^-]$ assessment throughout the entire incremental protocol to understand the resting intervals influence on each protocol step considering physiological and biomechanical responses;

(ii) Knowing that, the pulmonary VO_2 kinetics reflects on muscle VO_2 kinetics, future studies in swimming should implement the analysis of some intra-muscle parameters (e.g. PCr and PH), as has already been done in other cyclic sports, such as cycling and running;

(iii) Incorporation of a motion capture system to the biomechanical evaluation allowing a quasi-immediate 3D kinematical feedback on swimmers' technical adaptations;

(iv) Incorporation of surface electromyographic added to physiological, kinematical and external kinetics assessment to understand muscular adaptations in terms of amplitude, frequency and coordination during the intermittent incremental protocol;

(v) Optimization of the valve system to improve data internal validity;

(vi) Optimization of the VO_2 kinetics modelling equation, which should consider swimmers' hydrostatic weigth and horizontal position, since it becomes difficult to compare VO_2 kinetics parameters with other cyclic sports;

(vii) Development of a training program based on physiological and biomechanical data acquired during incremental protocol to analyse pre and post intervention effects;

(viii) Implementing bio-feedback system during intervention training program allowing swimmers to optimize the kinematic combinations for each speed selected;

(ix) Examining the relationships between EMG pattern of responses and power output in each step of incremental protocol and if slope and *y* intercept can change after intervention;

(x) Development of a normative physlogical and biomechanical data acquired during an incremental protocol for both genders and different competive events and levels during different training seasons.

Chapter 10 References

Chapter 1

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Chapter 7

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Appendix I

Different VO_2max time-averaging intervals in swimming.

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Abstract

We aimed to determine the effect of sampling interval strategy on VO_2max assessment to establish a standard time averaging method that allows a better identification of the VO_2 plateau incidence in swimming. To this end, 3 incremental protocols utilizing different step lengths for each sampling interval were used to compare VO_2max measurements. 11 trained male swimmers performed 3 repetitions of a front crawl intermittent incremental protocol until exhaustion (increments of 0.05 $m{\cdot}s^{-1}$, with 30 s and 24-48 h intervals between steps and tests, respectively) with 200, 300 and 400 m step lengths. VO_2 were directly measured, and 6 sampling intervals were compared: bxb and averages of 5, 10, 15, 20 and 30 s. Shorter sampling intervals (≤ 15 s) allowed the highest incidence of the VO_2 plateau, independently of the step lengths used; the 200 and 300 m step protocols accounted for higher percentage of VO_2 plateau incidence, and higher VO_2max values, comparing to the 400 m step protocol. As optimal sampling interval should be used for validation of the research findings, and considering that swimmers and coaches are more available for less time-consuming protocols, it is suggested the use of the 10 s time-average interval (once bxb and 5 s samplings presents high variability) in a 200 m step incremental protocol for VO_2max assessment in swimming.

Key words: swimming, maximal oxygen uptake, time-averaging, incremental protocol

Introduction

Since the pioneer work of Liljestrand & Strestrom, (1920), who measured the oxygen uptake (VO_2) of swimming in a lake, followed by sporadic studies in the 1940's (e.g. Karpovich & Milman, 1944) and 1960's (e.g. Astrand et al., 1963), the measurement of cardiorespiratory parameters (ventilatory volume, heart rate, and, especially, VO_2) have been a topic of swimming research (cf. the reviews Di Prampero, 1986, Holmér, 1974). Expanding on these previous studies, VO_2 measurement in swimming was frequently conducted in a flume or with a pulley system in a conventional pool, using a Douglas bag technique or a mixing chamber analyser. Looking for more ecological conditions, Toussaint et al. (1987) presented a respiratory snorkel and valve system with low hydrodynamic drag, which allowed continuous VO_2 measurement during conventional swimming in pools using different level swimmers (Fernandes at al., 2006; Fernandes et al., 2008; Vilas-Boas & Santos, 1994).

As the technology advanced, a portable gas analyser composed of a facemask, a flow meter, an O_2 gas analyser, and a telemetric receiver has been developed (Cosmed K2, Rome, Italy), and newer versions appeared (equipped with a CO_2 analyser) that allowed breath-by-breath data acquisition in swimming (Cosmed K4b2, Rome, Italy) (Fernandes et al., 2008; Reis et al., 2010). The widespread availability of modern breath-by-breath gas exchange systems enabled the acquisition of data with greatest precision and temporal resolution (Astorino, 2009; Duffield et al., 2004; Hill et al., 2003), and the improved instrumentation and technology in breath-by-breath analysis allowed new approaches to study cardiorespiratory parameters in laboratory and field conditions (Laffite et al., 2004; Reis et al., 2010).

From the traditionally assessed cardiorespiratory parameters, maximal oxygen consumption (VO_2max) has been lauded as an objective and reliable measure of the integrated maximal exercise response (Midgley et al., 2007), and is associated with the exercise intensity related to one of the primary areas of interest in swimming training and performance diagnostic (Astrand et al., 1963; Di Prampero, 1986; Fernandes et al., 2008; Holmér, 1974; Libicz et al., 2005). Despite being widely assumed as a standard of maximal aerobic power (Di Prampero, 1986; Fernandes et al., 2006; Fernandes et al., 2008; Holmér, 1974), and commonly accepted as a prerequisite for excellence in swimming (Fernandes et al., 2008; Sousa et al., 2011), there is no consensus on standardized criteria to verify VO_2max attainment at the end of an incremental exercise. In addition, the VO_2 kinetics measurement using the breath-by-breath technology has been also used to evaluate one major swimming performance determinant - the energy cost - through the percentages of VO_2max at different step intensities (Fernandes et al., 2006; Fernandes et al., 2008; Komar et al., 2012; Reis et al., 2010b; Reis et al., 2010a).

Essential to the utilization and interpretation of breath-by-breath technology in VO_2 related studies is the consideration of substantial inter-breath fluctuations of gas exchange during rest and exercise periods (Astorino et al., 2000; Midgley et al., 2007), which do not represent variations in O_2 loading in the lung or its utilization in the exercising muscles (Hill et al., 2003). In fact, when studying the VO_2 response to a specific effort, it is essential to analyse the variability on the VO_2 imposed by the chosen sampling interval (Dwyer, 2004). Multiple analysis strategies have been applied to inter-breath fluctuations to remove or reduce this source of imprecision, particularly by averaging the data from up to eight repetitions of the same step transitions (Astorino, 2009), and averaging across breaths or within discrete time intervals (Myers et al., 1990).

The impact of inter-breath variability in gas exchange has been addressed mainly for the heavy intensity domain, predominantly for the most accurate determination of VO_2max. Matthews et al. (1987) and Myers et al. (1990), for treadmill and ramp exercises (respectively), reported that ~20% difference in VO_2max could be attributed to differences in the method of sampling interval gas exchange data, and that the greatest VO_2max values were systematically higher as fewer breaths were included in an average. Astorino et al. (2000)] and Astorino

(2009) reported that sampling intervals dramatically influenced the incidence of the VO_2 plateau (the most used criterion for confirming the VO_2max attainment), and recommended short sampling intervals (≤ 15 s) when conducting incremental exercise to exhaustion. However, Midgley et al. (2007) evidenced that short time-average intervals appear to be inadequate in reducing the noise in pulmonary $\dot{V}O_2$, resulting in artificially high VO_2max values. Furthermore, Hill et al. (2003) reported high VO_2peak values at different intensities within the severe intensity domain when based on smaller sampling interval windows.

Specifically in swimming, the time-averaging method used to remove variation in breath-by- breath VO_2 has remained neglected when assessing VO_2max; in fact, only Sousa et al. (2010) analysed the VO_2max variability (using five different time-averaging intervals), observing higher VO_2 values for breath-by-breath sampling interval compared to time averages of 5, 10, 15 and 20 s in a 200-m all-out front crawl effort. Agreeing with the literature that the selection of optimal sampling interval strategy is fundamental to the validation of the research findings, as well as to the correct training diagnosis and posterior series intensity prescription, the aim of the present study was to establish a standard VO_2max time-averaging method that allow better identification of the incidence of the VO_2 plateau. For that purpose, six of the most used time-average intervals were compared: breath by breath and averages of 5, 10, 15, 20 and 30 s. As well, assuming that the step lengths used in the swimming incremental protocol for VO_2max assessment might affect the final result (as reported for running and cycling by Kuipers et al. (2003) and Hill et al. (2003), respectively), a comparison between the rate of VO_2max appearance when using 200, 300 and 400 m length steps was also accomplished, as these distances are the ones most used in the specialized literature (Fernandes et al., 2006; Fernandes et al., 2011; Komar et al., 2012; Libicz et al., 2005; Pyne et al., 2000; Reis et al., 2010; Vilas Boas & Santos, 1994). It was hypothesized that the VO_2max values would be greater when using shorter samplings intervals, particularly those ≤ 15 s, and that step lengths over 5 min duration (the 400 m steps) will imply a higher incidence of plateau in VO_2 at VO_2max.

Material and Methods

Participants

Eleven trained male swimmers volunteered for this study and signed an informed consent form before participation began. Individual and mean ± SD values for physical and performance characteristics were: 20.4 ± 2.5 years of age, 1.80 ± 0.06 m of height, 74.1 ± 4.1 kg of body mass, 11.3 ± 1.5 % of fat mass, 11.8 ± 3.2 years of training background, and 90.0 ± 4.1 % from the 200 m front crawl short course Word record. Body mass and fat mass were assessed through bioelectric impedance analysis method (Tanita TBF 305, Tokyo, Japan). All subjects were involved in systematic training (8 to 10 weekly training sessions) and competition programs - participating regularly in freestyle events. All the procedures were in accordance with the ethical standards proposed by Harriss & Atkinson, (2011).

Experimental procedure

Testing sessions took place in a 25 m indoor swimming pool, during the morning, with a room temperature of 28º C and humidity of 55%. Prior to the experiment, subjects were not engaged in high-intensity training sessions, and limited their training program to a single daily low-intensity swimming session. Swimmers performed, in a randomized order, three repetitions of a front crawl intermittent incremental protocol until exhaustion, each one with a different step length (200, 300 and 400 m); the protocol had velocity increments of 0.05 $m.s^{-1}$, with 30 s rest intervals between steps, and an interval of 24-48 h between each repetition. Researchers and coaches defined the velocity of the last step of the protocol through the 400 m front crawl best time that swimmers were able to accomplish at that moment (using in-water starts and open turns); then, six successive 0.05 $m.s^{-1}$ were subtracted from the swimming velocity corresponding to the last step, allowing the determination of the mean target velocity for each step (for a more detailed description see Fernandes et al., 2011). Underwater pacemaker lights (GBK-Pacer, GBK Electronics, Aveiro, Portugal), placed on the bottom of the pool, were used to help swimmers keep an even pace along each step, and change accordingly to the pace differences between steps. Swimmers breathed through a respiratory snorkel and valve system (the new AquaTrainer Snorkel®, Cosmed, Rome, Italy, cf. Baldari et al., 2001), connected to a telemetric portable gas analyzer ($K4b^2$, Cosmed, Rome, Italy). The $K4b^2$ apparatus was calibrated following the procedures described in the specialized literature (Duffield et al., 2004; Fernandes et al., 2008; Guidetti et al., 2008; Libicz et al., 2005; Reis et al., 2010). Atmospheric pressure and ambient temperature were measured by the $K4b^2$ portable unit, and relative humidity was measured and manually reported to the $K4b^2$ before each test. Heart rate was monitored and registered continuously by a heart rate monitor system (Polar Vantage NV, Polar electro Oy, Kempele, Finland) that telemetrically emitted the data to the $K4b^2$ portable unit. Capillary blood samples were collected from the earlobe during the 30 s intervals, immediately at the end of exercise, and during the 1st and 3rd min of the recovery period (Lactate Pro, Arkay, Inc, Kyoto, Japan).

Data analysis

VO_2 data analysis was centred in the step where VO_2max occurred. First, following Özyener et al. (2001), occasional breath values were omitted from the analysis by including only those in-between ± 4 standard deviation regarding the mean VO_2 value, once aberrant VO_2 values typically arise due to some constraints caused by the valve system and by swimming characteristics (e.g. longer apnea moments during the turns). Afterwards, individual breath-by-breath VO_2 responses were smoothed by using a 3-breath moving average and time-average (Fernandes et al., 2008) to produce a standard weighted response at 5, 10, 15, 20 and 30 s sampling intervals (an example of the VO_2 kinetics during the incremental protocol using breath-by-breath and 15 s sampling intervals is displayed in Figure 1). VO_2max was considered to be reached according to the occurrence of a plateau in VO_2, i.e., differences of $VO_2 \leq 2.1 ml \cdot kg^{-1} \cdot min^{-1}$ in the last 60 s of the step (between the final VO_2 value and the closest neighbouring data point), despite an eventual further increase in swimming velocity (Figure 1); if this was not observed, secondary criteria were applied, namely high levels of blood lactate concentration ($\geq$ 8 $mmol.l^{-1}$), elevated respiratory exchange ratio

(R ≥ 1.0), elevated heart rate [90% (220-age)], and an exhaustive perceived exertion, controlled visually and case-by-case (cf. (Fernandes et al., 2006; Fernandes et al., 2008; Howley et al., 1995; Libicz et al., 2005; Roels et al., 2005).

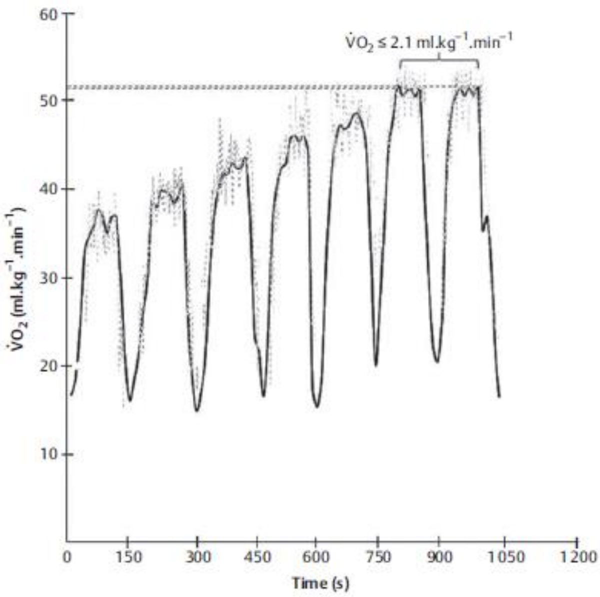

Figure 1. Example of the VO_2 kinetics along swimming incremental intermittent protocol for VO_2max assessment using breath-by-breath and 15 s sampling intervals (dotted and continuous lines, respectively). The occurrence of a VO_2 plateau during the 6th step is represented.

Statistical analysis

Data distribution was screened, and a non-normal distribution was observed through scatter plots and formal test (Shapiro-Wilk). VO_2 values were presented as median and interquartil range, and differences between time sampling intervals were tested for significance using the Friedman Multiple Comparison Test; the observed Z-scores for the dependent variable are based on positive or negative ranks, and significant differences are obtained if Z-score is in the [-1.96 to 1.96] interval. In addition, the Kendall $_W$ rank correlation coefficient values were also given; the coefficient of concordance must be in the range $-1 \leq {}_W \leq 1$, with higher values indicating a strong relationship. SYSTAT version 13.0 was used, and statistical significance was defined for $p < 0.05$.

Results

Individual VO_2max values occurred mostly in the sixth rather than in the seventh step in the 200 (n = 6 vs. 5), 300 (n = 9 vs. 2) and 400-m (n = 10 vs. 1) step lengths protocols. At the steps where VO_2max was obtained, the following median ± IQR values of blood lactate concentration, respiratory exchange ratio, and heart rate were observed: 8.22 ± 1.11, 8.41 ± 1.54 and 8.17 ± 1.24 $mmol.l^{-1}$, 1.15 ± 0.05, 1.18 ± 0.01 and 1.17 ± 0.02, and 187.6 ± 6.0, 182.4 ± 5.6 and 180.8 ± 3.8 bpm, respectively for the 200, 300 and 400 m step lengths protocols.

VO_2max values, assessed with different time sampling intervals (breath-by-breath and average of 5, 10, 15, 20 and 30 s) in the intermittent incremental protocol of 200, 300 and 400-m steps are displayed in Tables 1, 2 and 3, respectively. In Table 1 it was observed that: (i) breath-by-breath presented greater values than sampling intervals of 10, 15, 20 and 30 s (Zscore = 3.23, *P* = 0.00, Kendall's W = 0. 63; Zscore = 2.21, *P* = 0.00, Kendall's W = 0. 63; Zscore = 2.98, *P* = 0.00, Kendall's W = 0. 63; and Zscore = 3.04, *P* = 0.00, Kendall's W = 0. 63, respectively); (ii) 5 s time average presented greater values comparing to those of 20 and 30 s (Zscore = 2.78, *P* = 0.00, Kendall's W = 0. 63 and Zscore = 3.05, *P* = 0.00, Kendall's W = 0. 63, respectively). In addition, breath-by-breath and average of 5, 10, 15, 20 and 30 s sampling intervals accounted for a percentage of VO_2 plateau incidence of 27.2, 45.5, 72.7, 54.4, 18.1 and 18.1%.

Table 1. Individual and median ± interquatile range (IQR) values of VO_2max ($ml.min^{-1}.kg^{-1}$) at the incremental protocol of 200-m steps using different sampling intervals.

Subjects	Breath-by-breath	5s	10s	15s	20s	30s
A	56.83	56.71	56.32	55.21	54.14	53.25
B	51.56	51.21	51.33	51.57	51.78	51.45
C	52.81	52.33	52.45	52.52	52.44	51.77
D	51.08	49.75	49.49	49.47	49.63	49.85
E	48.99	45.69	45.09	46.05	44.01	44.04
F	53.95	53.71	53.58	53.86	53.60	53.62
G	54.15	52.19	52.27	51.78	52.46	51.57
H	52.21	53.12	52.65	54.19	52.74	52.23
I	53.04	50.17	49.36	50.16	49.31	49.68
J	51.30	53.6	51.73	51.22	50.44	49.10
K	51.80	52.04	51.16	51.50	50.74	51.09
Median ± IQR	53.23±2.21[a b c d]	52.13±3.14[c d]	51.64±3.31	51.15±3.26	51.11±3.21	51.08±3.36

[a b c d] Significantly different from time sampling interval of 10, 15, 20 and 30, respectively.

In Table 2 the data for the 300-m step lengths protocol is displayed, being possible to observe that breath-by-breath presented a higher value than time average of 20 and 30 s (Zscore = 2.95, *P* = 0.02, Kendall's W = 0.54; Zscore = 1.96, *P* = 0.05, Kendall's W = 0.54). Finally, breath-by-breath and average of 5, 10, 15, 20 and 30 s sampling intervals accounted for a percentage of VO_2 plateau incidence of 36.6, 45.5, 81.1, 54.4, 27.2 and 18.1%.

Table 2. Individual and median ± interquatile range (IQR) values of VO_2max ($ml.min^{-1}.kg^{-1}$) at the incremental protocol of 300-m steps using different sampling intervals.

Subjects	Breath-by-breath	5s	10s	15s	20s	30s
A	56.22	56.274	52.705	52.04	54.31	55.06
B	53.97	53.80	53.43	53.53	53.71	53.33
C	56.56	56.35	55.50	56.12	56.32	54.68
D	49.11	51.16	54.11	50.80	52.83	52.80
E	53.71	47.20	46.50	46.05	46.70	47.19
F	50.78	51.02	50.97	51.23	50.66	50.42
G	52.50	53.32	52.17	50.26	51.32	50.69
H	53.50	51.05	51.13	50.62	48.50	48.24
I	54.46	53.65	53.91	53.13	50.31	50.68
J	52.13	51.94	51.23	51.25	49.04	49.11
K	51.98	51.67	51.81	51.89	51.89	51.35
Median ± IQR	52.89±3.13[ab]	51.67±2.80	51.88±2.77	51.25±2.99	51.01±3.86	50.19±2.90

[a] Significantly different from time sampling interval of 30.

In the 400-m step lengths protocol (Table 3) breath-by-breath and 5 s time-averaging presented greater values than time averages of 20 and 30 s (Zscore = 3.03, *P* = 0.00, Kendall's W = 0.58 and Zscore = 3.05, *P* = 0.00, Kendall's W = 0.58, respectively), and breath-by-breath and average of 5, 10, 15, 20 and 30 s sampling intervals accounted for a percentage of VO_2 plateau incidence of 27.2, 36.3, 63.6, 45.5, 18.1 and 18.1%.

Table 3. Individual and median ± interquatile range (IQR) values of VO_2max ($ml.min^{-1}.kg^{-1}$) at the incremental protocol of 400 m steps using different sampling intervals.

Subjects	Breath-by-breath	5s	10s	15s	20s	30s
A	54.14	53.26	52.97	54.77	54.05	54.20
B	52.14	52.35	51.38	51.76	52.06	50.34
C	54.21	53.42	54.01	52.15	52.09	52.14
D	50.01	50.17	50.01	50.46	49.17	49.23
E	48.57	49.54	49.20	48.32	46.54	46.26
F	51.39	51.64	50.93	50.10	49.99	49.72
G	53.50	53.32	52.84	52.10	50.03	50.14
H	51.07	50.16	50.32	50.14	49.12	48.74
I	53.05	50.17	49.36	50.16	49.31	49.68
J	51.88	51.24	50.89	50.22	49.44	49.02
K	51.48	51.04	50.83	50.50	49.57	49.08
Median ± IQR	51.39±2.81[ab]	51.64± 2.90[ab]	50.93±3.30	50.46±3.19	49.72±2.64	49.13±3.74

[a,b] Significantly different from time sampling interval of 20 and 30 s, respectively.

Comparison between intermittent incremental protocols of 200, 300 and 400-m step lengths for the different studied VO_2 sampling intervals evidenced that: (i) when using breath-by-breath data, VO_2max median value obtained in the 300 m protocol was higher than that from the 400 m test (Zscore = 2.24, *P* = 0.04, Kendall's W = 0.28); (ii) when using 5 s average, VO_2max value of the 200 m protocol was higher than that obtained in the 400 m protocol (Zscore = 2.34, *P* = 0.04, Kendall's W = 0.31); (iii) regarding the 10 s time-averaging, no differences were observed in VO_2max values between protocols; (iv) averaging of 15 s indicated higher VO_2max values in the 200 m protocol than when using 400 m steps (Zscore = 2.36, *P* = 0.02, Kendall's W = 0.29); (v) considering the time average of 20 s, both 200 and 300 m protocols registered higher VO_2max values than the protocol with 400 m steps (Zscore = 2.17, *P* = 2.17, Kendall's W = 0.47 and Zscore = 2.34, *P* = 0.02, Kendall's W = 0.47, respectively); (vi) lastly, when using 30 s time-averaging, both 200 and 300 m protocols registered higher VO_2max values than 400 m test (Zscore = 2.08, *P* = 0.03, Kendall's W = 0.55 and Zscore = 3.29, *P* = 0.00, Kendall's W = 0.55, respectively).

Discussion

To our knowledge, this is the first study that compared VO_2max values, and examined the incidence of the VO_2 plateau, across various VO_2 sampling intervals, trying to propose a judicious time-averaging method to be used in VO_2max assessment in swimming. As the selection of optimal sampling interval strategies is a topic of great interest in laboratory exercise testing (cf. Astorino et al., 2000; Astorino, 2009; Hill et al., 2003), and is fundamental to validate its findings, the pertinence of this study in swimming is perfectly justified; in fact, the determination of the best sampling interval for VO_2max assessment is essential for a correct aerobic training status diagnosis, and posterior prescription of training.

The respiratory snorkel and valve system attached to the K4b2 was successfully used for swimming (Demarie et al., 2001; Komar et al., 2012; Libicz et al., 2005; Reis et al., 2010a; Reis et al., 2010b; Roels et al., 2005), allowing swimmers to perform their movements without restrictions (Roels et al., 2005). In fact, eventual differences in swimming velocity when comparing free swimming and swimming using the "old" AquaTrainer snorkel are not due to alterations on general kinematics or swimming efficiency but to the gliding phases after starts and turns (Barbosa et al., 2010); moreover, according to the manufacturer, the new AquaTrainer snorkel used in the current study is light, hydrodynamic, ergonomic and comfortable. K4b2 apparatus has been seen before as accurate and reliable (Demarie et al., 2001), and the exclusion of occasional breath values over 4 ± SD VO_2 values from the local mean significantly minimized occasional errant breaths in assessing VO_2max due to swallowing, coughing, sighing or some other reason unrelated to the physiological response of interest (Guidetti et al., 2008; Özyener et al., 2001). In addition, the smoothing of individual breath-by-breath VO_2 responses using a 3-breath moving average and time-average (Fernandes et al., 2008) allowed production of a standard weighted response at 5, 10, 15, 20 and 30 s sampling intervals, thereby reducing the "noise" and increasing the confidence of the parameter estimation.

The obtained VO_2max mean values in breath-by-breath and average of 5, 10, 15, 20 and 30 s sampling intervals, between ~49 and 53 $ml\cdot min^{-1}\cdot kg^{-1}$, were similar to those described in the literature for front crawl experienced male competitive swimmers (Demarie et al., 2001; Holmér, 1974; Libicz et al., 2005; Reis et al., 2012; Rinehardt et al., 1991; Roels et al., 2005), and lower than elite male swimmers (Fernandes et al., 2008; Laffite et al., 2004; Sousa et al., 2010; Sousa et al., 2011). The values of blood lactate concentration (between 8.0 and 12. $mmol.l^{-1}$), respiratory exchange ratio (from 1.11 to 1.17), and heart rate (comprehended between 181 and 207 bpm), corresponding to the step in which VO_2max was obtained by meeting the previously described criteria (Howley et al., 1995), and are also in accordance with the specialized literature (Demarie et al., 2001; Fernandes et al., 2006; Fernandes et al., 2011; Holmér, 1974; Laffite et al., 2004; Libicz et al., 2005; Reis et al., 2012; Rinehardt et al., 1991; Roels et al., 2005).

The primary aim of this study was to propose a judicious VO_2max time-averaging method that allows better identifying the incidence of the VO_2 plateau in swimming. Some laboratory studies were conducted previously, trying to verify the methodological factors that may affect the VO_2 kinetics, once it is well known that the manipulation of the sampling intervals may result in substantial VO_2 differences during incremental exercise testing (Astorino, 2009; Hill et al., 2003; Matthews et al., 1987; Myers et al., 1990). Our average results seem to corroborate these studies conducted in treadmill running and cycle ergometry, evidencing that lower sampling interval frequencies underestimate the VO_2max values; although the current study included only 11 swimmers, this fact was observed particularly for the 20 and 30 s averaging comparing to breath-by-breath data, independent of the step length used in the incremental protocol.

This was mathematically expected due to the greater temporal resolution that breath-by-breath sampling interval offers, allowing a better examination of small changes in VO_2 when performing at high intensities. However, the breath-by-breath gas acquisition could induce a significant VO_2 variability (Midgley et al., 2007), leaving the most appropriate sampling interval still unresolved. This is why some authors (e.g. Hill et al., 2003) underlined the importance of analysing the impact of inter-breath variability in gas exchange, which might not represent the variations in oxygen loading in the lung or its utilization in the exercising muscles. According to the obtained results, the 5, 10 and 15 s time averages seems to be the best to use as a standard VO_2max time-averaging method, corroborating the literature for ergometer exercise (Astorino et al., 2000; Astorino, 2009; Midgley et al., 2007). As the 10 s sampling interval obtained the highest incidence of the VO_2 plateau, independently of the step lengths used, we suggest its use when assessing VO_2max in swimming. However, it is important to highlight that some authors, studying other sports than swimming, did not use time average intervals to assess VO_2 kinetics but the mean of 3, 5 or 10 breaths (Hill et al., 2003). Thus, future studies should have this in mind, and also try to increase the number of subjects tested.

In addition, the percentage of VO_2max occurrence in protocols with 200, 300 and 400 m step lengths was examined. Traditionally, VO_2max (or VO_2peak) assessment protocols in swimming use steps ≥ 4 min (Holmér, 1974; Reis et al., 2010a; Reis et al., 2010b; Troup & Daniels, 1986), which, according to some authors (Rinehardt et al., 1991; Troup & Daniels, 1986), is necessary to cause a temperature increase and a pH decrease in the muscle, fostering an environment which is optimal for oxygen extraction. As the longer steps are more likely to produce a physiological steady state (Pyne et al., 2000; Reis et al., 2010), it was hypothesized that the 400 m steps implied a higher incidence of plateau in VO_2 at VO_2max; however, independent of the time average used, it was observed that the 400 m step never accounted for a higher percentage of occurrence of plateau at VO_2max than the other step lengths; the 200 and 300 m steps accounted for a similar percentage of VO_2 plateau incidence, with higher percentages in the breath-by-breath and 10 and 20 s sampling intervals for the 300 m comparing to the 200 m step protocol.

Lastly, the 400 m step protocol presented lower VO_2max values, comparing to the 200 and 300 m step lengths, whatever the time-average intervals used (with exception with the 10 s sampling interval, in which no differences were observed). Obtaining lower mean peak VO_2 in protocols with 6 min duration comparing to that with 1 min steps, Kuipers et al. (2003) warned that incremental exercise protocols with relatively long duration of each step may prevent achievement of peak values of VO_2 and heart rate because of premature fatigue. In fact, 200 and 300 m step lengths were used in some recent studies that implemented intermittent incremental swimming protocols for VO_2max assessment (Fernandes et al., 2008; Komar et al., 2012; Libicz et al., 2005; Pyne et al. 2000; Reis et al., 2012; Reis et al., 2010a; Roels et al., 2005), as well as in not so recent ones (Vilas Boas & Santos, 1994); in addition, a previous comparison between 200, 300 and 400 m step protocols and a maximal lactate steady state test concluded that the use of 200 and 300 m step lengths are valid for individual anaerobic threshold assessment, and that the 400 m step distance underestimate the blood lactate concentrations corresponding to that parameter (Fernandes et al., 2011).

Nevertheless the low number of swimmers of the current sample, the above-referred facts suggests that 200 and 300 m step length could be used instead of 400 m steps, both for VO_2max and anaerobic threshold assessment. Furthermore, the shorter 200 m steps are more specific to the training and competitive requirements of swimmers (Pyne et al., 2000; Sousa et al., 2011), and, the use of this step distance for VO_2max assessment in swimming, represents a compromise between a metabolic steady state, and swimming velocities more specific to competition.

Conclusions

The results of this study indicate that shorter sampling intervals (≤ 15 s) allowed the highest incidence of the VO_2 plateau, independent of the step lengths used, and that the 200 and 300-m step protocols accounted for higher percentage of O_2 plateau incidence, and higher VO_2max values, compared to the 400 m step protocol. As an optimal sampling interval should be used, and considering that swimmers and coaches are more engaged in testing programs if the swimming distance is not long (better integrating with their workout schedule), it is proposed that use of the 10 s time-average interval in an 200 m step incremental protocol for VO_2max assessment in swimming. It is suggested, for future studies conducted in larger samples, to test if the 10 s time-average interval is the most proper to use along an incremental test with 200 m steps, as it is known that distinct exercise intensities (moderate, heavy and severe) implies different VO_2max kinetics.

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Appendix II

Effect of protocol step length on biomechanical measures in swimming.

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Abstract

The assessment of energetic and mechanical parameters in swimming often requires the use of an intermittent incremental protocol, whose step lengths are corner stones for the efficiency of the evaluation procedures. The aim of this research was to analyse the existence of changes in swimming kinematics and inter-limb coordination behavior in 3 variants, with different step lengths, of an intermittent incremental protocol. Twenty-two male swimmers performed $n \cdot d_i$ variants of an intermittent and incremental protocol ($n \leq 7$; d_1 = 200 m, d_2 = 300 m and d_3 = 400 m). Swimmers were videotaped in the sagittal plane for 2D kinematical analysis using a dual-media set-up. Video images were digitized with a motion capture system. Parameters which were assessed included the stroke kinematics, the segmental and anatomical landmark kinematics, and inter-limb coordination. Movement efficiency was also estimated. There were no significant variations in any of the selected variables according to the step lengths. A high-very high relationship was observed between step lengths. The bias was much reduced and the 95% CI fairly tight. Since there were no meaningful differences between the 3 protocol variants, the one with shortest step length (i.e. 200 m) should be adopted due to logistic reasons.

Key words: front crawl, stroke mechanics, kinematics, efficiency, index of coordination

Introduction

Nowadays, training prescription in elite sports is a research-based practice. Since the number of youth willing to train swimming hardly, everything indicates that the swimming sport becomes more egalitarian. Training control and evaluation assesses the likelihood of a given outcome (i.e. performance) to be achieved, thereby helping coaches to design training sets in accordance. In the case of individual, closed and cyclic sports (as competitive swimming and open water), energetics, mechanics and motor control play a relevant part in such likelihood (Barbosa et al., 2010a). To understand such interactions, literature suggests the application of experimental protocols where variables from all those fields of knowledge are assessed concurrently [e.g., (Figueiredo et al., 2013; Oliveira et al., 2012; Pyne et al., 2000)]. Most of these protocols are characterized by a number of incremental (from a low to maximal intensity) steps to characterize the swimmer's energetic and technical profile (Pyne et al., 2000; Fernandes et al., 2005). The length of the protocol's steps is still a controversial issue, as it is required a balance between the time necessary for stabilization of a given variable to be assessed, the time spent to conduct the data collection (Pyne et al., 2000; Fernandes et al., 2005). On the one hand, eager coaches would take the results from the test, on the other, they have the feeling of spending too much time with the testing procedures. Protocol's step lengths are selected from a range between 200 to 400 m (roughly 3 to 7 min or less, depending on the swimmer's competitive level).

Traditionally, incremental protocols have been implemented without stopping the exercise, and continuously increasing the intensity between steps. However, in swimming, the implementation of (short) rest intervals between steps is required so that the swimmer can receive proper feedback, and researchers can collect capillary blood (to assess some energetics outcomes as the lactate kinetics and energy cost of locomotion) and, eventually, control swimming intensity through rate of perceiving exertion (Fernandes et al., 2005). When comparing the effect of different step lengths (200 vs. 300 vs. 400 m) of an intermittent incremental protocol, Fernandes et al. (2011) observed that the velocity and the heart rate corresponding to individual anaerobic threshold, as well as the blood lactate concentrations and heart rate maximal values were similar among protocol's variants. The only exception was the higher blood lactate concentration values at individual anaerobic threshold in the 200 m and 300 m variants compared to the 400 m one. Focusing mainly at energetics, Fernandes et al. (2012a) reported that incremental protocol variants with 200 and 300 m steps accounted for higher percentage of oxygen uptake plateau incidence and higher maximal oxygen consumption values compared to the 400 m step protocol. These authors concluded that, from an energetics point of view, 200 m would be the most suitable to be used, as it would decrease the time needed to individually assess swimmers, with no significant impact on validity and accuracy of data collected.

Stroke mechanics (Figueiredo et al., 2013; Seifert et al., 2007), segmental kinematics (Komar et al., 2012; Seifert et al., 2010; Zamparo et al., 2009) and anatomical landmarks (e.g. hip) or centre of mass kinematics (Barbosa et al., 2008b) are monitored on regular basis in competitive swimming. There is a solid body of evidence about the relationship of these variables with swimming performance. Swimming efficiency is another topic of interest as it is a determinant factor as well (Barbosa et al., 2006; Toussaint et al., 2004; Zamparo et al., 2005). More recently, inter-limb coordination became as part of the assessment portfolio of most research and practitioners protocols (Figueiredo et al., 2013; Komar et al., 2012; Seifert et al., 2004). Therefore, the variables selected for this research are useful and informative for coaches and swimmers.

Several biomechanic and motor control variables are also monitored during this step tests, such as: (i) stroke kinematics (e.g. stroke frequency, stroke length and mean swim velocity) (Barbosa et al., 2008a; Fernandes et al., 2010; Fernandes et al., 2011; Figueiredo et al., 2013); (ii) segmental and anatomical kinematics (e.g. body velocity, and hands and feet velocity) (Barbosa et al., 2008b); (iii) swim efficiency (e.g. speed fluctuation and stroke index) (Barbosa et al., 2006); and (iv) inter-limb coordination (e.g. index of coordination) (Figueiredo et al., 2013; Komar et al., 2012). To select a protocol variant with shorter steps it is necessary that its length would not affect significantly energetics, kinematics and inter-limb coordination. As seen before, energetics seems not to be significantly affected by the cut down of the step length (Fernandes et al., 2011; Fernandes et al., 2012a), but it is questionable if shorter step lengths (i.e. 200 m) will affect the swimmer's kinematics and motor control. There is some body of knowledge reporting that a relationship exists between the energetic and the biomechanical behaviors. However, there is a time gap or delay between the on-set and stabilization of parameters from both fields (i.e. the stabilization of biomechanics and energetic variables happen at different moments). Moreover the on-set of fatigue might also occur in different moments. Hence, it is not so straightforward that changes in the biomechanics and motor control behavior are completely coupled to the energetic one.

As no research comparing the swimmers kinematics and motor control behaviors during an intermittent incremental protocol with different step lengths has been done, it was purposed to compare protocol variants with different steps lengths in order to observe possible changes in technique related parameters. It was hypothesized that there are no significant differences in the kinematics and inter-limb coordination variables induced by shorter to longer step lengths, and, for pragmatic reasons, a shortest step distance should be selected.

Method

Participants

Twenty-two sub-elite swimmers (mean±SD: 20.78±5.31 years-old, 1.78±0.06 m of height, 71.40±5.72 kg of body mass, 1.81±0.07 m of arm span) voluntarily participated in the present study. Swimmers attend on regular basis to national and international level competitions (%WR: 79.90±9.61%; PB: 254.90 ±20.39s). All the procedures described below were approved by the Institutional Ethics Committee and followed the Helsinki Declaration regarding human experiments.

Participants were completely informed about the procedures and demands of the study and signed a written informed consent, approved by the Institutional Ethics Committee.

Procedure

All test sessions took place in a 25 m indoor swimming pool, 1.90 m deep, with water temperature at 27.5°C. A standardized warm-up, consisting of 1000 m of aerobic swimming of low-to-moderate intensity, was conducted before each variant of the protocol. Using in water starts and flip turns, each participant performed, in randomized order, 3 variants of the front crawl intermittent incremental protocol until exhaustion, with different step lengths: $n{\cdot}d_i$ ($n \leq 7$: d_1=200 m, d_2=300 m, and d_3=400 m). The swim pace of each step was common to the 3 protocol variants and controlled through a visual pacer (TAR. 1.1, GBK-electronics, Aveiro, Portugal) with flashing lights on the bottom of the pool. The last step pace was predefined as the swimmer's personal best at 400-m front crawl swimming at that time of the experiments. Then, 0.05 $m.s^{-1}$ was successively subtracted, allowing the determination of the mean target velocity for each step of the incremental protocol (Fernandes et al., 2005; Fernandes et al., 2011). In addition, elapsed time for each swim was hand-timed with a stopwatch (Seiko) to assess the exact swimmer's speed. A 48 h rest period was respected between each protocol variant and swimmers were asked to abstain from strenuous exercise during this period. All subjects were able to perform 7x200 m and 7x300 m, but only 8 swimmers completed totally the 7th step of the 7x400 m protocol variant at the pre-defined velocity.

Data collection

Swimmers were videotaped in the sagittal plane for 2D-kinematical analysis using a dual-media set-up, with two cameras (Sony, DCR-HC42E, Nagoya, Japan) operating at a sampling frequency of 50 Hz, with 1/250 of digital shutter speed, fixed on a specially designed support for video imaging recording(Fernandes et al., 2012b; Figueiredo et al., 2013). This support was placed at the lateral pool wall, 12.5 m from the head wall, with one camera placed 30 cm above the water surface and the other kept underwater in a waterproof housing (Sony SPK-HCB box) at a depth of 0.30 m, exactly below the surface camera (both placed at 7 m from the plane of movement). The images of both cameras were recorded independently, and swimmers were monitored when passing through a specific pre-calibrated space using a calibration frame (6.3 m^2). Each camera recorded a space of 4.5 m long for the x-axis, and participants wear specific anatomical markers on upper limbs and trunk. It was used the anthropometric model from Zatsiorsky & Seluyanov (1983) adapted by de Leva (1996), including nine anatomical landmarks from the upper body (acromion, lateral humeral epicondyle, ulnar styloid process, third distal phalanx and prominence of great femoral trochanter). Synchronization of the images was obtained using a pair of LEDs, fixed to the calibration volume, visible in the field of view of each camera. The frame was kept in the same place during all trials. Video images were digitized manually frame-by-frame (f=50 Hz) using a motion capture system (Ariel Performance Analysis System, Ariel Dynamics, USA). The analysis period comprised one complete stroke cycle in the penultimate lap of each step for each protocol variant (i.e., 175 m, 275 m and 375 m). Swimmers were instructed to perform non-breathing cycles when passing in the calibrated space since the breathing action imposes changes in the technique turning out to be a potential confounding factor that must be controlled. Six calibration points and DLT-algorithm (Abdel-Aziz & Karara,1971) were used for 2D-reconstruction. The selection of a 5 Hz cut-off value for data filtering (with a low pass digital filter) was done according to residual analysis (residual error vs. cut-off frequency). Root Mean Square (RMS) reconstructions errors of six validations points on the calibration frame (which did not serve as control points) were (for horizontal and vertical axes, respectively) accurate: (i) 1.92 mm and 1.78 mm, representing 0.33 and 0.40% of calibrated space for above water; and (ii) 1.84 mm and 1.71 mm, representing 0.38 and 0.43% of the calibrate space for underwater.

Each swimmer's stroke kinematics were assessed according to: (i) stroke frequency (SF), the inverse of the time needed to complete one full stroke cycle; (ii) stroke length (SL), the horizontal displacement of the right hip during one stroke cycle; (iii) speed (v), assessed by the product between SF and SL. Segmental and anatomical landmark kinematics were also determined: (i) absolute trunk inclination with horizontal plane (TI), calculated as the average value, over one stroke cycle, of the angle between the shoulder and the hip segment and the horizontal at the end of insweep of the arm pull (Zamparo et al., 2009); (ii) right hip average speed (v_{hip}), computed by dividing the swimmer's average hip horizontal displacement by the time required to complete one stroke cycle; (iii) average horizontal right and left swimmer's hands speed (u_r and u_l), as the right and left hands speed during the underwater propulsive phases (pull and push). For the efficiency estimation the following parameters were determined: (i) stroke index (SI), calculated by the product between SL and v; (ii) intracycle speed variation of the horizontal displacement of the hip (dv), computed as the coefficient of variation of the instantaneous speed-time data for horizontal axis; (iii) dv normalized to swim speed (dv/v); (iv) difference between maximal and minimal v_{hip} within the stroke cycle (Δv); (v) Δv normalized to swim speed (Δv/v); (vi) arm's propelling efficiency (η_F) (Zamparo et al., 2005); (vii) propulsive efficiency (η_p) (Toussaint et al., 2004).

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

To determine the accuracy of the digitizing procedure, two repeated digitization of a randomly selected trial were selected, and the coefficients of repeatability with limits of agreement (95%) were calculated using Bland-Altman method: (i) 0.00835 $m.s^{-1}$ [-0.0071 to 0.0098] for the horizontal hip's speed; (ii) 0.0022 m [-0.0026 to 0.0035] for hip's horizontal displacement; and (iii) horizontal hand's speed 0.00996 $m.s^{-1}$ [-0.0091 to 0.0113]; (iv) 5.32 °[-4.52 to 6.81] for trunk inclination.

Statistical analysis

The normality and homoscedasticity assumptions were checked with the Kolmogorov-Smirnov and the Levene tests, respectively. Mean±2SD (corresponding approximately to 95% CI) are reported whenever appropriate. Inferential data analysis included: (i) analyzing data variation; (ii) computing simple linear regression models; (iii) computing Bland-Altman plots; and (iv) testing differences in variance (Pitman's test). Comparison between step lengths was done with ANOVA 2-ways (step length x step number) ($P \leq 0.05$). Simple linear regression model between pairwise step lengths (i.e. 200 m vs. 300 m, 200 m vs. 400 m and 300 m vs. 400 m) were computed, including the coefficient of determination (r^2) and error of estimation (s). As a rule of thumb, for qualitative interpretation, it was defined that the relationship was: (i) very weak if $r^2<0.04$, weak if $0.04 \leq r^2<0.16$, moderate if $0.16 \leq r^2<0.49$, high if $0.49 \leq r^2<0.81$ and very high if $0.81 \leq r^2<1.0$. Bland-Altman analyses were used to assess the bias±1SD, as well as the 95% confidence interval for such bias between pair-wise step lengths. Pitman's test was also used as complement to ANOVAs testing to analyze the difference in variance between protocols (i.e. 200 m vs. 300 m, 200 m vs. 400 m and 300 m vs. 400 m).

Results

For the step number effect, regarding the stroke kinematics (Fig. 1) there is a trend for the SF and v increase, while SL decreases (all for $P < 0.001$).

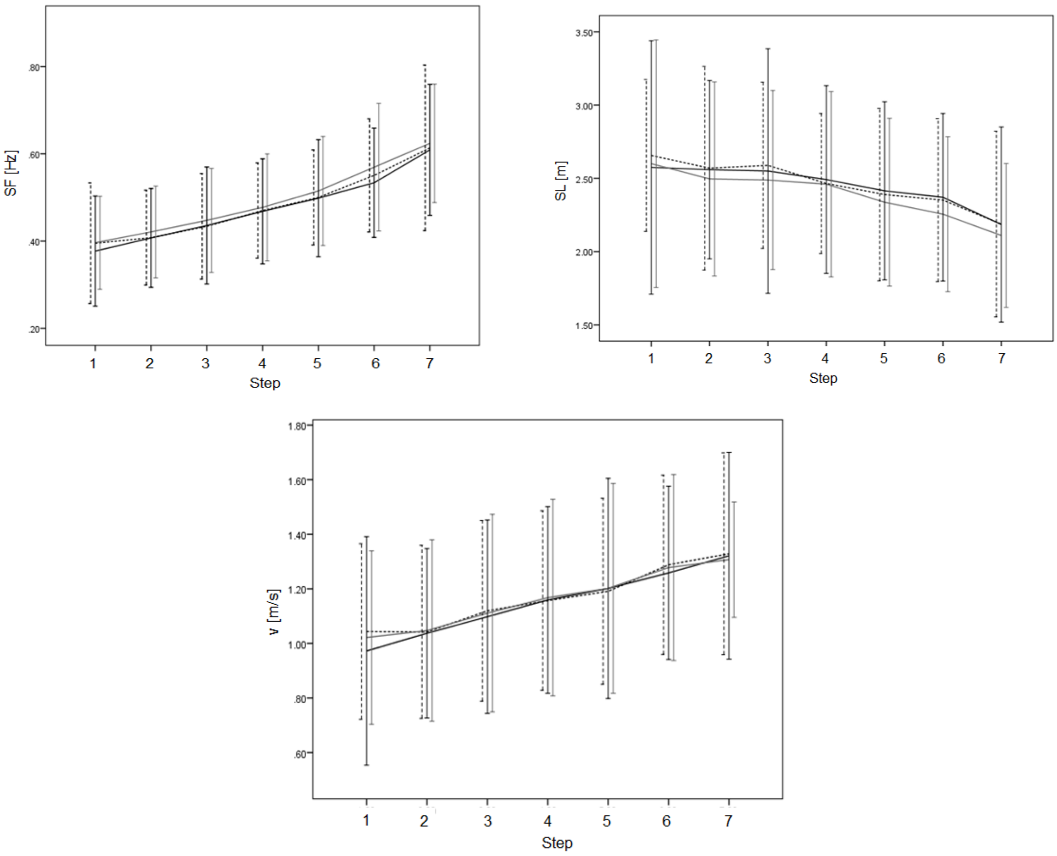

Figure 1. Mean ± 2SD (i.e ~95% CI) for the variation of the stroke kinematics during the 200 (black solid line), 300 (black dashed line) and 400-m (grey solid line) step lengths**.** Stroke Frequency (SF), stroke length (SL), speed (v).

For segmental and anatomical landmark kinematics (Fig. 2) there is an increase of v_{hip}, u_l and u_r (all for $P < 0.001$) throughout the protocol. The same trend was observed for the IdC ($P < 0.001$), but always in a catch-up coordination mode (Fig. 3). Concerning swimming efficiency (Fig. 3) there are mixed trends: while most variables suggest an increase in the efficiency (η_F and dv/v, $P < 0.001$; Δv/v, $P = 0.05$), others showed no significant variations (SI, dv and Δv). Interestingly, the last ones are those that were not normalized to the swim pace.

Considering the step length x step number, there were no significant interactions in any of the selected dependent variables. Indeed, a visual inspection of the 2SD bars (i.e. ~95 CI) reveals that for all variables, variation profiles were very similar.

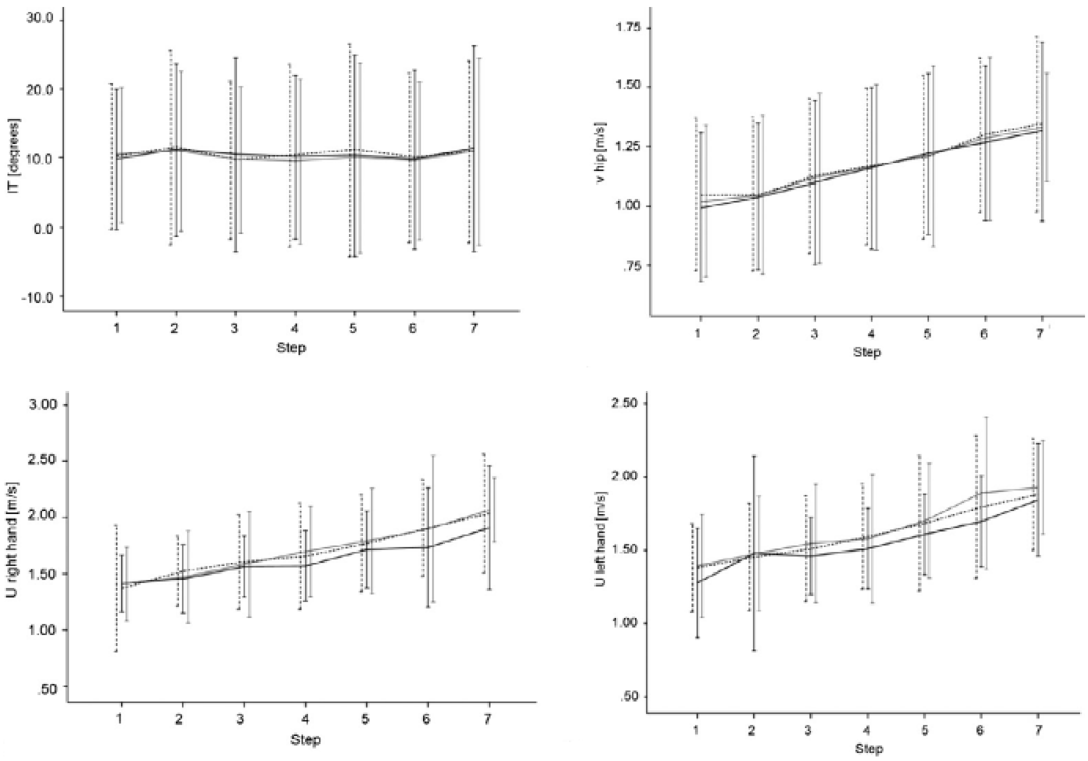

Figure 2. Mean ± 2SD (i.e ~95% CI) for the variation of the segmental kinematics during the 200 (black solid line), 300 (black dashed line) and 400-m (grey solid line) step lengths**.** trunk inclination (TI), hip´s speed (v_{hip}), average horizontal right and left swimmer's hands speed (u right, u left respectively).

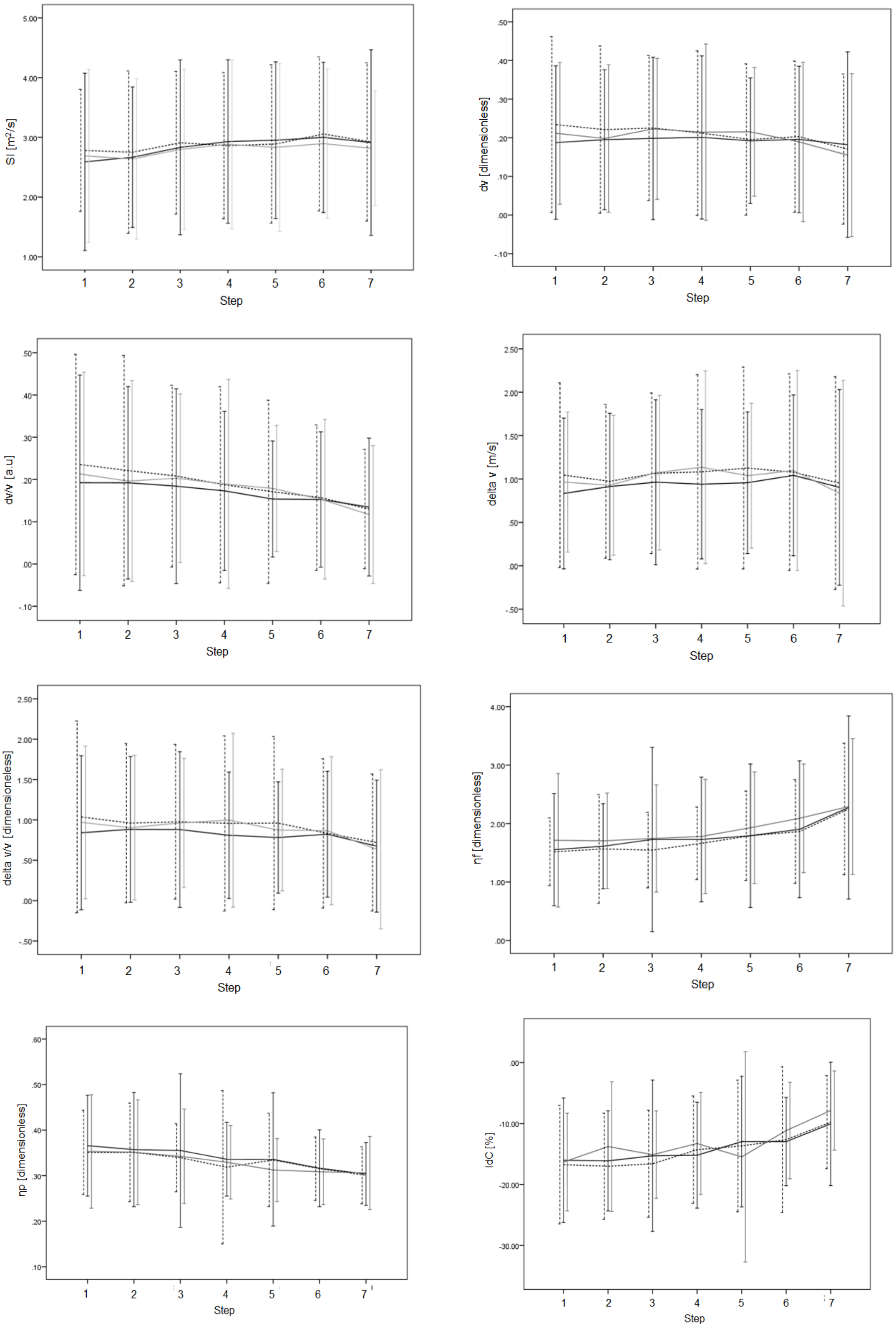

Figure 3. Mean ± 2SD (i.e ~95% CI) for the variation of the swimming efficiency and inter-limb coordination during the 200 (black solid line), 300 (black dashed line) and 400-m (grey solid line) step lengths. Stroke index (SI), intracycle speed variation of the horizontal displacement of the hip (dv), dv relative to swim speed (dv/v), difference between maximal and minimal hip´s speed

within the stroke cycle (Δv), Δv relative to swim speed (Δv/v), propulsive efficiency (η_p), arm´s propelling efficiency (η_F) and index of coordination (IdC).

Most variables presented a high-very high relationship, with the highest associations for the v and v_{hip} and the lowest for the Δv ($0.44 \le r^2 \le 0.89$; $0.24 \le s \le 0.06$) (Table 1). Regarding the Bland-Altman tests, the bias was much reduced and the 95% CI was fairly tight for all selected variables (Table 1). Lastly, the Pitman´s test was not significant for most of the variables (Table 1).

Table 1. Regression models and bias assessment for the selected dependent variables.

		200 vs 300-m	200 vs 400-m	300 vs 400-m
SF	r^2	0.73	0.76	0.86
	s	0.05	0.04	0.03
	Bias ± SD	-0.001 ± 0.043	-0.008 ± 0.038	0.01 ± 0.0400
	95% CI upper;lower	- 0.08;0.08	-0.08;0.06	-0.10;0.08
	Pitman's test	0.10 (*P*=0.34)	0.12 (*P*=0.24)	0.03 (*P*=0.80)
SL	r^2	0.55	0.64	0.72
	s	0.22	0.19	0.15
	Bias ± SD	-0.010 ±0.190	0.030±0.310	0.041±0.272
	95% CI upper;lower	-0.40;0.37	-0.59;0.65	-0.51;0.60
	Pitman's test	0.12 (*P*=0.28)	0.11 (*P*=0.32)	0.02(*P*=0.84)
v	r^2	0.85	0.85	0.89
	s	0.07	0.07	0.06
	Bias ± SD	-0.004±0.060	0.008±0.110	0.01±0.091
	95% CI upper;lower	-0.13;0.12	-0.21;0.23	-0.17;0.19
	Pitman's test	0.05 (*P*=0.62)	0.03 (*P*=0.76)	0.03 (*P*=0.80)
TI	r^2	0.69	0.55	0.69
	s	3.63	4.52	3.14
	Bias ± SD	-0.26±3.170	0.033±3.991	0.236±3.341
	95% CI upper;lower	-6.61;6.07	-7.96;8.03	-6.44;6.92
	Pitman's test	0.12 (*P*=0.28)	0.27 (*P*=0.01)	0.21 (*P*=0.05)
dv	r^2	0.66	0.52	0.59
	s	0.04	0.04	0.05
	Bias ± SD	-0.0027±0.04	-0.0033±0.04	0.0047±0.04
	95% CI upper;lower	-0.08;0.08	-0.08;0.08	-0.09;0.10
	Pitman's test	0.21 (*P*=0.09)	0.02 (*P*=0.86)	0.17 (*P*=0.15)
dv/v	r^2	0.71	0.61	0.72
	s	0.05	0.06	0.05
	Bias ± SD	0.001±0.049	0.0037±0.052	0.0025±0.057
	95% CI upper;lower	-0.09;0.09	-0.10;0.11	-0.11;0.11
	Pitman's test	0.21 (*P*=0.08)	0.04 (*P*=0.73)	0.18 (*P*=0.12)
Δv	r^2	0.57	0.44	0.63
	s	0.23	0.24	0.28
	Bias ± SD	-0.021±0.232	-0.0079±0.187	0.0329±0.227
	95% IC upper;lower	-0.48;0.44	-0.38;0.37	-0.42;0.49
	Pitman's test	0.23 (*P*=0.06)	0.08 (*P*=0.51)	0.34 (*P*=0.01)
Δv/v	r^2	0.69	0.47	0.64
	s	0.21	0.26	0.28
	Bias ± SD	0.0139±0.217	0.00142±0.226	0.0443±0.265
	95% CI upper;lower	-0.44;0.42	-0.45;0.45	-0.49;0.58
	Pitman's test	0.29 (*P*=0.02)	0.05 (*P*=0.67)	0.25 (*P*=0.03)
SI	r^2	0.66	0.79	0.79
	s	0.37	0.30	0.27
	Bias ± SD	-0.037 ±0.326	0.0275±0.245	0.058±0.241
	95% CI upper;lower	-0.69;0.62	-0.46;0.52	-0.43;0.54
	Pitman's test	0.01 (*P* =0.95)	0.03 (*P*=0.81)	0.04 (*P*=0.74)
η_p	r^2	0.50	0.51	0.51

	s	0.04	0.04	0.03
	Bias ± SD	0.00581±0.0389	0.0084±0.0348	-0.000061±0.033
	95% CI upper;lower	-0.07;0.083	-0.06;0.07	-0.06;0.06
	Pitman's test	0.42 (*P*=0.01)	0.37 (*P*=0.01)	-0.08 (*P*=0.47)
η_F	r^2	0.50	0.71	0.76
	s	0.42	0.30	0.20
	Bias ± SD	0.0400±0.356	-0.0425±0.229	-0.0591±0.250
	95% CI upper;lower	-0.67;0.75	-0.52;0.43	-0.56;0.44
	Pitman's test	0.37 (*P*=0.01)	0.35 (*P*=0.01)	-0.06 (*P*=0.54)
u_r	r^2	0.55	0.66	0.73
	s	0.14	0.14	0.15
	Bias ± SD	-0.0287±0.171	0.0018±0.198	0.0113±0.128
	95% CI upper;lower	-0.37;0.32	-0.39;0.39	-0.24;0.26
	Pitman's test	-0.09 (*P*=0.42)	0.18 (*P*=0.13)	0.09 (*P*=0.42)
u_l	r^2	0.59	0.60	0.68
	s	0.14	0.15	0.13
	Bias ± SD	-0.015±0.127	-0.137±0.127	-0.0136±0.268
	95% CI upper;lower	-0.27;0.24	-0.26;0.24	-0.54;0.52
	Pitman's test	0.06 (*P*=0.61)	-0.01 (*P*=0.95)	-0.08 (*P*=0.45)
v_{hip}	r^2	0.78	0.89	0.89
	s	0.08	0.06	0.06
	Bias ± SD	-0.0109±0.077	-0.0011±0.0052	0.0083±0.0535
	95% CI upper;lower	-0.13;0.14	-0.11;0.10	-0.03;0.11
	Pitman's test	0.07 (*P*=0.50)	0.07 (*P*=0.50)	0.07 (*P*=0.50)
IdC	r^2	0.65	0.54	0.63
	s	4.20	4.42	4.35
	Bias ± SD	-0.661±6.090	-1.140±5.248	-0.596±5.082
	95% CI upper;lower	-11.51;12.84	-11.63;9.35	-10.76;9.56
	Pitman's test	0.12 (*P*=0.29)	0.01 (*P*=0.90)	0.15 (*P*=0.18)

Stroke Frequency (SF), stroke length (SL), speed (v), trunk inclination (TI), intracycle speed variation of the horizontal displacement of the hip (dv), dv relative to swim speed (dv/v), difference between maximal and minimal hip´s speed within the stroke cycle (Δv), Δv relative to swim speed (Δv/v), stroke index (SI), propulsive efficiency (η_p), arm´s propelling efficiency (η_F), average horizontal right and left swimmer's hands speed (u_r, u_l), hip´s speed (v_{hip}) and index of coordination (IdC).

Discussion

The aim of this study was to analyze the kinematics and inter-limb coordination changes of a typical intermittent incremental protocol (with different step lengths: 200 m vs. 300 m vs. 400 m). Main findings were: (i) no significant variations between step lengths for selected variables; (ii) a high-very high relationship/agreement between conditions; (iii) a reduced bias and a fairly tight 95CI; (iv) few differences were verified for the variance tested with Pitman's test. Overall, since there were no-significant differences between step lengths, the shortest one (i.e. 200 m) should be adopted, as it less time-consuming and matches most race distances.

Support staff has a very limited time to evaluate athletes as priority is for the training, making this a challenging task. Testing sessions should be as less disruptive as possible of the training session and probably be considered in the periodization. Overall, there are no meaningful kinematical and motor control differences when selecting 200 m, 300 m and 400 m step lengths in a typical swimming intermittent incremental protocol. Hence, the 200 m step length is a feasible option since such length it is less time-consuming, then remaining ones. Same finding was reported for the assessment of selected energetic variables (Fernandes et al., 2011; Fernandes et al., 2012a; Fernandes et al., 2012c). Therefore, from an holistic point of view the 200m step length seem to be a well-rounded and comprehensive away to monitor the at the same time the energetic, biomechanics and motor control profiles.

A concurrent analysis of kinematics, efficiency and energetics provides a deeper insight about swimmers' fitness status and performance level. It was observed that the kinematics and motor control behavior was similar to what was reported for the n·200 m and other step lengths. The SF and v increase while SL decreases slightly (Barbosa et al., 2008a; Figueiredo et al., 2013; Fernandes et al., 2011; Fernandes et al., 2010; Psycharakis et al., 2008). The v_{hip}, u_l and u_r increase (Barbosa et al., 2006; Komar et al., 2012; Seifert et al., 2010). It was reported changes in the swimming efficiency (Oliveira et al., 2012; Toussaint et al., 2004); besides the fact that IdC increases (Figueiredo et al., 2013; Komar et al., 2012). Interestingly swimmers showed always a catch-up coordination mode during the intermittent incremental protocol. It is well-known that this coordination mode is selected more often at slow swim paces. As swim pace or speed increases the trend is for a shift from catch-up to opposition and superposition. This time around swimmers were unable to do such shift throughout the protocol. One might expect that at the end of the protocol, they would have a superposition coordination mode. This can be due to several reasons including the task constraint (i.e., the imposed pace for each step; the maximal effort asked after having swim five to six steps at a vigorous intensity). The swimmers assessed in this study presented a technical profile very similar to what was reported before for 200 m step lengths.

Moreover, there were no-significant step lengths (200 m vs. 300 m vs. 400 m) x step number (n≤7) interactions for all variables.

The selected variables presented a high-very high relationship, a low error of estimation, reduced bias, the 95 CI fairly tight and lower differences in variance. Even though there is a high-very high relationship between step lengths, 11 out of 15 biomechanical parameters showed relationships below R^2=0.7 between 200 and 300 step lengths, and 12 out of 15 biomechanical parameters showed the largest relationships between the 300 and 400 step lengths. The difference in the association level between 200 v 300m and 300 v 400m ranges between -5% and 17%. However remaining selected statistics (standard error of estimation, Bland-Altman plots, 95% confidence interval and Pitman's test) suggest a very high adherence between step lengths, being the bias residual. Hence, we should exercise some care performing the analysis of different step lengths based on one single statistical outcome. A deeper insight can be obtained from the overall analysis of the major trend of all statistics. On top of that, data reported in table 1 can be used to correct under/overestimations whenever necessary and appropriate. Coaches are looking forward for less time-consuming, less expensive and less complex procedures. On the other side, researchers are willing to collect valid, reliable and accurate data. The need to compromise coaches and researchers expectations leaves no option than reduce the step lengths and thereafter correct bias. This type of bias corrections happens on regular basis in fields such as anthropometrics (Morais et al., 2011), kinematics (Barbosa et al., 2010b; Fernandes et al., 2012b) and energetics (Baldari et al., 2009; Fernandes et al., 2005). Therefore, whenever the 200 m step length are used, after data collection researchers or sports analysts can use data from Table 1 as a way to correct potential bias.

Despite no significant differences were reported between step length protocols, only 8 swimmers completed the 7th step of the 7x400 m protocol variant at the predefined velocity. Even though there is no obvious trend in the characteristics of these swimmers (3 are national level swimmers and 5 international level; 4 are sprinters and 4 are middle-distance swimmers) one might consider that some step lengths are more suitable for than others according to the swimmers' characteristics (e.g., distance, stroke, gender, competitive level, etc).

An important concern for coaches when testing athletes is to obtain the most relevant information about a given swimmer. Therefore, in a near future it would be interesting to examine if there is any relationship between step length and the swimmers' specialty (e.g., stroke, distance or gender). Another important concern for coaches is that the testing procedures should not disrupt the training program. Therefore, longer distances (for example 400 m) would be suitable to insert the step test into a training session. By performing, 7x400 at different intensities swimmers would be completing an ideal distance for a middle-distance swimmer main training set (i.e., 2800 in total). At least very high level swimmers might be able to perform such kind of sets. Finally, a number of repetitions on the low-medium intensities could be also recommended for some swimmers (12x200 instead of 7x200 step test) in order to maintain the training volume.

It is interesting to note that others suggested different protocols to assess swimmers. E.g., a 2x400 m 2-speed test is also very popular among practitioners since it also enables to monitor and prescribe different training intensities (Olbrecht et al., 1988). However, the common ground across all these testing procedures is to tailor customized training sets based on energetic and biomechanics measures (Olbrecht & Mader, 2006). Same framework can also be selected for age-group swimmers but with other procedures, such as the critical speed tests, T30 or T3000.

Despite the novelty of this research, some limitations should be pointed out. It was performed a 2D-kinematical analysis while swimming is a typical 3D-movement (Figueiredo et al., 2012; Seifert et al., 2010). So some precaution should be used when extrapolating these findings to 3D-kinematics. Swimmer's displacement and velocity, was assessed by the hip instead of the centre of mass. It was reported a ~3% and ~7% bias for the displacement and velocity between both landmarks, respectively (Fernandes et al., 2012b). Finally, the response of other motor control variables (e.g. the neuro-muscular activity) was neglected as goes beyond the aim of this study. Data collected in short-course meter swimming pool might be different from what is expected if testing procedures are carry out in long-course meter or short-course yards swimming pools. Hence, follow-up and intervention programs should select always the same type of swimming pool.

Conclusions and practical applications

There are no meaningful kinematical and inter-limb coordination differences between the three step lengths selected on regular basis when designing a swimming intermittent and incremental protocol. Most of the times, swimmers' evaluation happens during training session or training camps. Sport science staff is keen to select less time-consuming procedures. Therefore, a protocol with shorter step length (i.e. 200 m) can be adopted. It will be spend less time with data collection having a minimum effect in the data internal validity. Even so, whenever required a higher accuracy, data can be corrected based on the data reported in this paper.

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Appendix III

Comparison between aerobic power parameters at different time-averaging intervals in swimming: an update.

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Abstract

Sousa et al. (Open Sports Sci J, 3: 22 – 24, 2010) showed that different time averaging intervals lead to distinct VO_2 values in a maximal 200m front crawl effort, evidencing higher VO_2 values for breath-by-breath sampling, and differences between this latter data acquisition and all the other less frequent time intervals studied (5, 10, 15 and 20 s). These are interesting outputs in the field of exercise physiology applied to swimming once: (1) VO_2 assessment is conducted in a swimming pool with a portable gas analyser which allowed breath-by-breath measurements, and not in a swimming flume with a Douglas bag technique or mixing chamber analyser, as traditionally occurs, and (2) the comparison between different time-averaging intervals used to remove breath-by-breath fluctuations during exercise periods has remained neglected, in sport in general and swimming in particular. Therefore, in the present study, we investigate the influence that different time averaging intervals have in aerobic power related parameters (VO_2peak and VO_2max). Ten subjects performed 200m front crawl effort at supra-maximal intensities (all-out test) and other ten subjects performed 200m front crawl effort at maximal aerobic intensities (100% of VO_2max).The intensity at which the 200m front crawl was performed (supra-maximal and maximal intensities) had a significant effect on VO_2peak and VO_2max values obtained for each averaging intervals studied.

Key words: swimming, time- average intervals, VO_2peak, VO_2max

Introduction

The goal of competitive swimming is to obtain the fastest speed of locomotion during a race, being success determined by several influencing factors, particularly the energetic and biomechanical ones. This is possible to infer from the swimming performance equation: v = E * (ept / D), where v is the swimming velocity, E represents the energy expenditure, ept is the propulsive mechanic efficiency and D represents the hydrodynamic drag (Pendergast et al., 1977). Among the evaluation of the energetic factors, the assessment of maximal oxygen uptake (VO_2max) is a key point of contemporary research in sport science in general and in "swimming science" in particular (Fernandes & Vilas Boas, 2012). Considered to express the maximal metabolic aerobic performance capability of a subject, the VO_2max assessment is crucial for a better understanding of human energetics, and therefore, is related to one of the primary areas of interest in swimming training and performance diagnoses (Fernandes & Vilas Boas, 2012; Sousa et al., 2011).

Acknowledging that the evaluation of aerobic performance is very relevant for swimming training purposes, it is important to study the specific VO_2 kinetics at different swimming intensities. In fact, the physiology of a maximal performance encompasses distinct neuromuscular processes, intramuscular energy turnover, cardiovascular and respiratory elements, which interconnect differently across different swimming intensities (Aspenes & Karlsen, 2012). Furthermore, when studying the VO_2 response to a specific effort it is essential to analyze the variability on the VO_2 data imposed by the used sampling intervals (Dwyer, 2004). In fact, the selection of optimal sampling intervals strategy is fundamental to the validation of the research findings, as well as to the correct training diagnosis and posterior prescription of the intensity of the training series (Fernandes et al., 2012). (Myers et al., 1990) reported 20% of variability on the VO_2 values due to different chosen data sampling intervals, and that the greatest VO_2max values were systematically higher as fewer breaths were included in an average. (Midgley et al., 2007) evidenced that short time-average intervals appear to be inadequate in reducing the noise in pulmonary VO_2, resulting in artificially high VO_2max values. Moreover, (Hill et al., 2003) showed higher peak VO_2 (VO_2peak) values at different intensities when based on smaller sampling intervals. These last referred studies (Hill et al., 2003; Midgley et al., 2007; Myers et al., 1990) were conducted in laboratory conditions, not in real swimming situation.

Regarding swimming, only our group (Fernandes et al., 2012; Sousa et al., 2010) analyzed the VO_2 variability when considering distinct time averaging intervals, but different swimming intensities were never compared. In this sense, the purpose of this study is to compare the variability of the VO_2 values obtained in a 200m front crawl effort performed at maximal and supra-maximal aerobic intensities, using five different time averaging intervals: breath-by-breath and average of 5, 10, 15, and 20 s, respectively. We hypothesized that the different intensity performed in the 200m front crawl would lead to significant effect on VO_2peak and VO_2max values obtained for each averaging intervals.

Methods

Participants

Ten male well trained swimmers (20.5 ± 2.3 years old, 185.2 ± 2.3 cm, 77.4 ± 5.3 kg and 10.1 ± 1.8% of fat mass) and ten trained male swimmers (20.7 ± 2.8 years old, 182.0 ± 0.1 cm, 75.2 ± 4.1 kg and 11.1 ± 1.6% of fat mass) volunteered to participate in (Sousa et al., 2010) and (Fernandes et al., 2012) studies, respectively. All subjects were informed of the protocol before the beginning the measurement procedures, and were usually involved in physiological evaluation and training control procedures.

Procedures

Both studies were conducted in a 25 m indoor swimming pool, 1.90 m deep, water temperature of 27.5ºC and humidity of 55%. In (Sousa et al., 2010) each swimmer performed an all-out 200 m front crawl (with an individual freely chosen pace).

VO_2peak was accepted as the highest single value on breath-by-breath, 5, 10, 15 and 20 s sampling obtained. In (Fernandes et al., 2012), each swimmer performed a 7x200 m front crawl intermittent incremental protocol until exhaustion, with 30 s rest intervals and with velocity increments of 0.05 $m \cdot s^{-1}$ between each step. The velocity of the last step was determined through the 400 m front crawl best time that swimmers were able to accomplish at that moment (using in-water starts and open turns); then, 6 successive 0.05 $m \cdot s^{-1}$ were subtracted from the swimming velocity corresponding to the last step, allowing the determination of the mean target velocity for each step. This was controlled by underwater pacemaker lights (GBK-Pacer, GBK Electronics, Aveiro, Portugal), placed on the bottom of the pool. VO_2 data analysis was centred in the step where VO_2max occurred, being this considered as the average values of the breath-by-breath, 5, 10, 15 and 20 s sampling obtained.

As swimmers were attached to a respiratory valve (cf. Figure 1), allowing measuring the VO_2 kinetics in real time, open turns without underwater gliding and in-water starts were used. For a detailed description of the breathing snorkels used in the supra-maximal and maximal intensities cf. (Keskinen et al., 2003) and (Fernandes & Vilas Boas, 2012), respectively. These respiratory snorkels and valve systems were previously considered to produce low hydrodynamic resistance and, therefore, not significantly affect the swimmers performance. VO_2 kinetics was measured breath-by-breath by a portable metabolic cart ($K4b^2$, Cosmed, Italy) that was fixed over the water (at a 2 m height) in a steel cable, allowing following the swimmer along the pool and minimizing disturbances of the swimming movements during the test.

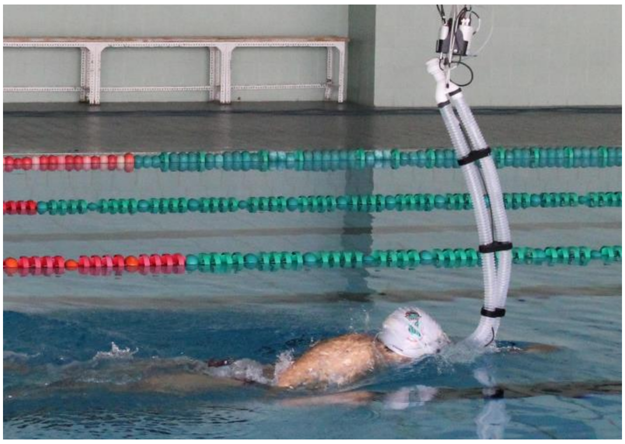

Figure 1. Specific snorkel and valve system for breath-by-breath VO_2 kinetics assessment in swimming.

Statistical analysis

Mean ± SD computations for descriptive analysis were obtained for the studied variable using SPSS package (version 14.0 for Windows). In addition, ANOVA of repeated measures was used to test: (i) the differences between the five different sampling intervals considered in the maximal and supra-maximal intensity, and (ii) the interaction effect of intensity in the VO_2 values in the five different sampling intervals studied. When a significant F value was achieved, Bonferroni post hoc procedures were performed to locate the pairwise differences between the averages. A significance level of 5% was accepted. Since a limited sample was used, effect size was computed with Cohen's f. It was considered (1) small effect size if $0 \leq |f| \leq 0.10$; (2) medium effect size if $0.10 < |f| \leq 0.25$; and (3) large effect size if $|f| > 0.25$ (Cohen, 1988).

Results

The VO_2 values (expressed in $ml \cdot kg^{-1} \cdot min^{-1}$) obtained in the breath-by-breath, 5, 10, 15 and 20 s time averaging intervals studied in the 200 m front crawl effort performed at supra-maximal (Sousa et al., 2010) and maximal aerobic intensities (Fernandes et al., 2012) are presented in Figure 2.

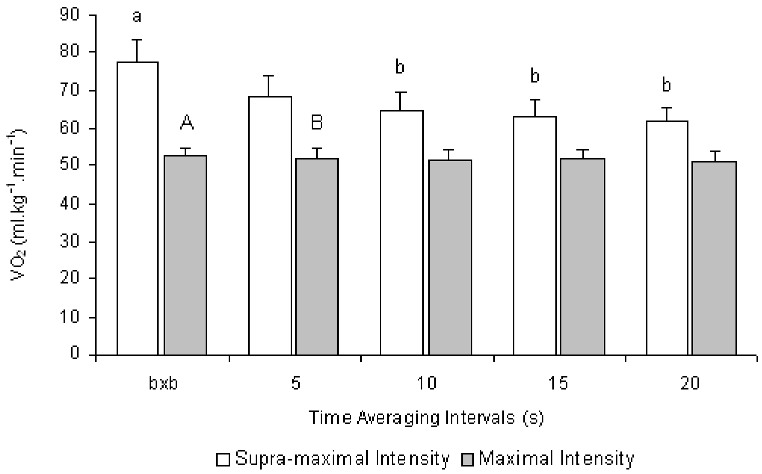

Figure 2. VO_2 values (expressed in $ml \cdot kg^{-1} \cdot min^{-1}$) obtained in the breath-by-breath, 5, 10, 15 and 20 s time averaging intervals studied in the 200 m front crawl effort performed at supra-maximal (Sousa et al., 2010) and maximal aerobic intensities (Fernandes et al., 2012). Bars indicate standard deviations. [a] Significantly different from time averaging interval of 5, 10, 15 and 20 s, [b] Significantly different from time averaging interval of 5s, [A] Significantly different from time averaging interval of 10, 15 and 20 s, respectively, [B] Significantly different from time averaging interval of 20 s. $P < 0.05$.

In (Sousa et al., 2010), VO_2peak ranged from 61.1 to 77.7 to $ml.kg^{-1}.min^{-1}$ ($F_{(1.82;\ 16.38)} = 59.55$, $P < 0.001$, $f = 0.86$). Higher VO_2peak values were reported for breath-by-breath interval, being observed differences between the 5 s averaging interval and the other less frequent data acquisitions considered (10, 15 and 20 s). In (Fernandes et al., 2012), VO_2max ranged from 51.1 to 53.2 $ml.kg^{-1}.min^{-1}$ ($F_{(2.18;\ 19.63)} = 4.12$, $P < 0.05$, $f = 0.31$). The breath-by-breath time interval was only significantly different from the three less frequent averaging intervals studied (10, 15 and 20 s), being also reported differences between the 5 and 20 s intervals methods. The intensity at which the 200 m front crawl was performed (supra-maximal and maximal intensities) had a significant effect on VO_2peak and VO_2max values obtained for each averaging intervals studied ($F_{(1.87;\ 33.75)} = 44.15$, $P < 0.001$, $f = 0.71$).

Discussion

It is well accepted that for modern diagnostics of swimming performance, new more precise and accurate analytical techniques for VO_2 kinetics assessment are needed. In fact, after the Douglas bags procedures, VO_2 became to be directly assessed using mixing chamber's devices, and only afterwards an upgrade enabled real time breath-by-breath data collection with portable gas measurement systems (Fernandes et al., 2013). Furthermore, this improvement also allowed testing in normal swimming pool conditions, overlapping the standard laboratory conditions that do not perfectly reflect the real-world performances (Fernandes et al., 2008; Fernandes & Vilas Boas, 2012; Sousa et al., 2011). The VO_2peak mean value obtained in (Sousa et al., 2010) study was similar to those described in the literature for experienced male competitive swimmers (Fernandes et al., 2008; Rodríguez & Mader, 2003), but higher than the VO_2max mean value reported by (Fernandes et al., 2012).This may be due to the different intensity domain in which both efforts occurred. In fact, the sudden and exponential increase in VO_2 that occurs close to the beginning of the effort at intensities above VO_2max triggers the attainment of high VO_2 values (Sousa et al., 2011). Moreover, the intensity at which the 200 m front crawl was performed (supra-maximal and maximal intensities) had a significant effect (71%) on VO_2peak and VO_2max values obtained for each sampling intervals studied.

Regarding the primary aim of the current study, both (Fernandes et al., 2012; Sousa et al., 2010) studies corroborate the specialized literature conducted in other cyclic sports (namely treadmill running and cycle ergometer), which state that less frequent sampling frequencies underestimate the VO_2 values (Astorino & Robergs, 2001; Astorino, 2009; Myers et al., 1990). Regarding the swimming specialized literature, both studies are unique and both reported that the breath-by-breath acquisition presented greater values than sampling intervals of 10, 15 and 20 s. This fact seems to be explained by the greater temporal resolution that breath-by-breath sampling offers, allowing a better examination of small changes in high VO_2 values. However, it should be taken into account that the breath-by-breath gas acquisition could induce a significant variability of the VO_2 values acquired. Moreover, while (Sousa et al., 2010) evidenced significant differences between the two shortest sampling intervals (breath by breath and 5s), (Fernandes et al., 2012) only reported significant differences between the breath by breath and time sampling interval of 10, 15 and 20 s, and between time sampling interval of 5 and 20 s. These apparently incongruent results may be due to the distinct swimming intensities at which both efforts occurred.

In conclusion, we have shown that the intensity at which the 200 m front crawl was performed (supra-maximal and maximal intensities) had a significant effect on VO_2peak and VO_2max values obtained for each averaging intervals studied, still being unanswered which of the models tested is the most appropriate sampling interval to be used. In this sense, in VO_2peak and VO_2max assessment it must be taken into account the intensity at which the effort occurred because this may lead to distinct averaging intervals strategies. At supra-maximal intensity, and considering the higher ventilation, respiratory frequency and VO_2, the possibility of selecting an artifact with lower averaging intervals (e.g. breath-by-breath), is higher. Such fact is clearly stated in the significant difference between VO_2peak values obtained (ranging from 61.1 to 77.7 to $ml \cdot kg^{-1} \cdot min^{-1}$). At maximal intensities, being this range lower (51.1 to 53.2 to $ml \cdot kg^{-1} \cdot min^{-1}$), the associated error is less obvious. A limitation to our study is the fact that the swimmers who performed the 200 m front crawl at supra-maximal intensity were not the ones that held the 200 m at maximal intensity.

Such lack of uniformity could lead to inter individual differences possible to interfere in the VO_2peak and VO_2max values obtained. Future research about this topic, also conducted in ecologic swimming conditions, i.e., in swimming-pool (not in laboratory based ergometers and swimming flumes) is needed. Although VO_2 is difficult to measure due to technical limitations imposed by the swimming pool and the aquatic environment, its assessment in non-ecological conditions could influence the VO_2max, compromise the assessment of the corresponding velocity at VO_2max (vVO_2max) and the time to exhaustion at vVO_2max. These two latter problems could induce errors in training intensities prescriptions. In this sense, the most advanced (valid, accurate and reliable) monitoring methods that could be used during actual swimming must be used in order to assess VO_2 in ecological swimming conditions, allowing more reliable, accurate and valid results.

The selection of optimal sampling strategies is fundamental to the validation and comparison of research findings, as well as to the correct training diagnosis and training intensities prescription. Literature results should be taken with caution when comparing VO_2peak and VO_2max values assessed with different sampling intervals and in different intensity domains. In addition, a standardized criterion should be found to accurate set the VO_2peak and VO_2max that removes the possibility of selecting an artifact.

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Appendix IV

Oxygen uptake kinetics at moderate and extreme swimming intensities.

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Abstract

Traditionally, studies regarding oxygen consumption kinetics are conducted at lower intensities, very different from those in which the sports performance occurs. Knowing that the magnitude of this physiological parameter depends on the intensity in which the effort occurs, it was intended with this study compare the oxygen consumption kinetics in the 200 m front crawl at two different intensities: moderate and extreme. Ten international male level swimmers two separate tests by 24 h: (i) progressive and intermittent protocol of 7 x 200 m, with 30 seconds intervals and with increments of 0.05 $m \cdot s^{-1}$, to determine the anaerobic threshold correspondent step; and, (ii) 200 m at maximal velocity: in both expiratory gases were continuously collected breath-by-breath. Significant differences were obtained between amplitude and time constant determine in the 200 m at extreme and moderate intensities, respectively (38.53 ± 5.30 $ml \cdot kg^{-1} \cdot min^{-1}$ *versus* 26.32 ± 9.73 $ml \cdot kg^{-1} \cdot min^{-}1$ e 13.21 ± 5.86 s *versus* 18.89 ± 6.53 s ($P \leq 0.05$). No differences were found in time delay (9.47 ± 6.42 s *versus* 12.36 ± 6.62 s), at extreme and moderate intensity, respectively ($P \leq 0.05$). A negative correlation between time delay and time constant at the moderate intensity was reported ($r = -0.74$, $P \leq 0.05$).

Key words: swimming, VO_2 kinetics, moderate intensity, extreme intensity

Introduction

The magnitude and nature of the adjustment of the oxygen consumption (VO_2) at the beginning of any physical exercise strongly depends on the intensity at which the effort is performed (Jones & Burnley, 2009). In fact, at moderate intensities, where exercise is performed below the anaerobic threshold, the VO_2 reaches a quick balance state after a single growth phase, which is named fast component (Burnley & Jones, 2007). At high intensity though, for example, above the anaerobic threshold, the VO_2 kinetics reveals a new phase – the slow component –, which, when appearing after the fast component, delays the onset of the balance state of VO_2 (Barstow & Mole, 1991). At severe intensities, where exercise is performed significantly above the anaerobic threshold, the VO_2 and blood lactate values ([La-]) are not able to stabilize, and therefore, the VO_2 kinetics exposes two components (fast and slow), finishing the exercise before it is possible to obtain a balance state (Gaesser & Poole, 1996). Although it has been described very recently, the extreme intensity domain, being performed at intensity above maximal oxygen consumption (VO_2max), reflects the intensity at which the majority of the competitive efforts occur (Burnley & Jones, 2007). However, few studies have been conducted in this domain, being almost unexplored in swimming, especially at higher intensities.

The aim of the present work is to analyze and compare the VO_2 kinetics at two distinct swimming intensities, in conditions as close as possible to the ones obtained during competition: (i) moderate intensity, analyzing 200 m *crawl* at intensity corresponding to the individual anaerobic threshold – lan_{ind}); and (ii) extreme intensity, evaluating 200 m *crawl* swam at maximum intensity.

Methods

10 male swimmers of international level participated in this study. The individual and mean (± sd) values of their main physical characteristics and of competitive

swimming practice are presented in table 1. The body weight and fat mass values were determined through bioelectrical impedance (Tanita TBF 305, Tokyo, Japan). All subjects were previously informed about the details of the experimental protocol before the data collection, having offered their written consent for the participation. The protocol was approved by the ethics committee of the local Institution.

Table 1. Individual and mean (± SD) values of the main physical characteristics and sports performance of the swimmers.

Swimmer	Age (yrs)	Height (m)	Weight (kg)	Fat Mass (%)	Points Len 200m	Years of Training (yrs)	% World Record 200m
#1	17	1.77	68.1	12.5	1707.0	8	80.6
#2	24	1.82	73.4	9.2	1376.2	17	88.8
#3	24	1.92	81.5	9.1	1480.3	17	86.1
#4	19	1.78	73.7	12.8	1752.7	8	79.6
#5	22	1.84	75.2	9.7	1511.5	15	85.3
#6	21	1.89	74.6	10.1	1794.7	13	78.6
#7	22	1.72	74.2	13.6	1906.7	13	76.2
#8	16	1.87	81.0	11.2	1734.8	7	79.9
#9	21	1.82	72.3	12.3	1688.6	12	81.0
#10	21	1.83	78.4	11.2	1622.5	15	82.4
Mean (±sd)	20.71 (±2.82)	1.82 (±0.06)	75.24 (±4.07)	11.17 (±1.60)	1657.5 (±160.7)	12.50 (±3.71)	81.9 (±3.9)

Instruments and procedures

All experimental sessions occurred in an indoors 25 m acclimatized swimming pool (27ºC), with relative humidity of 45%. Each subject performed two distinct protocols in the *crawl* style, and an interval of 24 hours between them was respected. A progressive and interval protocol of 7 x 200 m, with 30 s interval with increments of 0.05 $m{\cdot}s^{-1}$ between each step (Fernandes et al., 2003; Fernandes et al., 2008). The velocity of the last step was determined according to the performance hypothetically reached at that time at 400 m crawl, subtracting later to six intensity thresholds; swimming velocity was controlled with a light pacer (TAR 1.1, GBK – electronics, Aveiro, Portugal), placed in the bottom of the pool. This test was used to determine the 200 m which was closer (or coinciding) with the velocity corresponding to the lan_{ind}, 24 hours after that, the 200 m crawl at maximum velocity was performed (Sousa et al., 2011). In both protocols, the starts were performed from the water, and the swimmers were told to perform open laps, always to the same side and without gliding. The VO_2 was measured through continuous expired gas collection breath-by-breath through a portable gas analyzer (K4b^2, Cosmed, Italy), which was connected to the swimmer through a respiratory tube and valve considered suitable for ventilatory gas parameters collection in swimming situations (Baldari et al., 2011). All that experimental equipment was lifted 2 m above the water surface on a steel cable, which made it possible to follow the swimmer along the pool, minimizing discomfort to the swimmer's movements (figure 1).

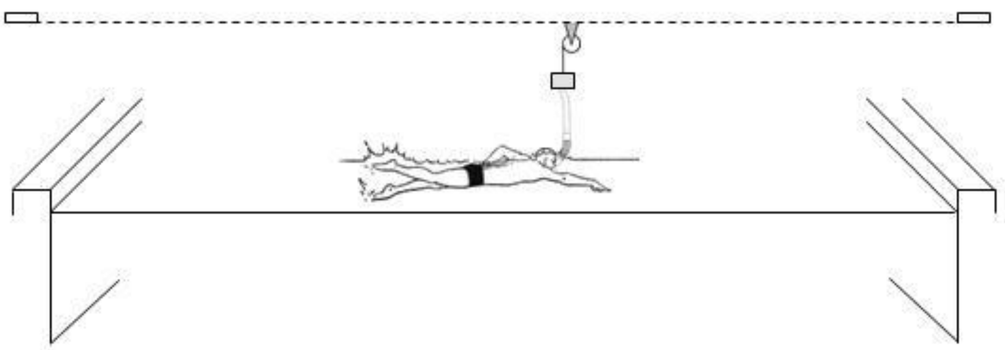

Figure 1. Experimental instrument used for collection of ventilatory gas

In order to minimize the noise resulting from the gas collection breath-by-breath, data were then edited to exclude faulty breathing (e.g. coughing), which do not realistically represent the subjacent kinetics, being only considered the values comprised between the mean ± four standard deviations (Özyener et al., 2001). Subsequently, the data obtained breath-by-breath were softened through a movable mean of three breaths (Guidetti et al., 2008) and recorded in mean periods of five seconds (Sousa et al., 2010), increasing the validity of the estimated parameter. Capillary blood was collected from the earlobe and used to determine the [La-] using a portable analyzer (Lactate Pro analyzer, Arcay, Inc). The collections occurred before each protocol, during the recovery periods (incremental protocol) and at the end of them (at minutes 1, 3, 5 and 7 of recovery). The [La-] enabled the determination of lan_{ind}, in the incremental protocol through the [La-] curve modelling *versus* velocity, assuming it was the interception point of the best adjustment of linear and exponential regressions used for determination of the exact point of the beginning of exponential increase of [La-] (Fernandes et al., 2012; Machado et al., 2006). In all swimmers from the sample, the inflexion point of the [La-] occurred at the 4th step of the incremental protocol. Heart rate values were continuously monitored (at each five seconds) through a monitor system (Polar Vantage NV, Polar Electro Oy, Kempele, Finland).

In order to analyze the VO_2 kinetics, the curves considered (from the 200m corresponding to the lan_{ind} and from 200 m at maximal velocity) were modelled considering a mono-exponential fitting (Equation 1):

$$VO_2(t) = VO_{2b} + A_1 * (1 - e^{-(t - TD_1/\tau_1)}) \quad \textbf{(1)}$$

Where t is the time (s), V_b is the VO_2 value at the beginning of the exercise ($ml.kg^{-1}.min^{-1}$), A is the amplitude of the fast component ($ml.kg^{-1}.min^{-1}$), TD is time of beginning of the fast component (s) and t is the time constant of the fast component (s), i.e., the time needed to reach 63% of the plateau of this phase. Additionally, the VO_2 curves corresponding to the Ian_{ind} were also modelled considering two exponential phases (equation 2 – bi-exponential):

$$VO_2(t) = VO_{2b} + A_1 * (1 - e^{-(t - TD_1/\tau_1)}) + A_2 * (1 - e^{-(t - TD_2/\tau_2)}) \quad \textbf{(2)}$$

Where t is the time (s), V_b is the VO_2 value at the beginning of the exercise ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$), A_1 and A_2 are the amplitude of the fast and slow components ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$), TD_1 and TD_2 are the times of the beginning of the fast and slow components (s) and t_1 and t_2 are the time constants of the fast and slow components (s), respectively. The linear method of the minimum squares was implemented in the Matlab program for the adjustment of this function to the VO_2 data.

Statistical analysis

The *F*-Test (P = 0.91) presented the homogeneity of the variance of the monoexponential and bi-exponential models used to analyze the 200 m *crawl* performed at the intensity corresponding to the Ian_{ind}, which was confirmed by the equality of mean values through the *T*-Test (P = 0.97). Thus, in the present study the VO_2 kinetics at moderate and extreme intensities seem to be well-described by a monoexponential function, not being positive to use a bi-exponential function. Figure 2 presents two illustration curves of the VO_2 kinetics of one swimmer, in the 200 m corresponding to the Ian_{ind}, and in the 200 m performed at maximum intensity.

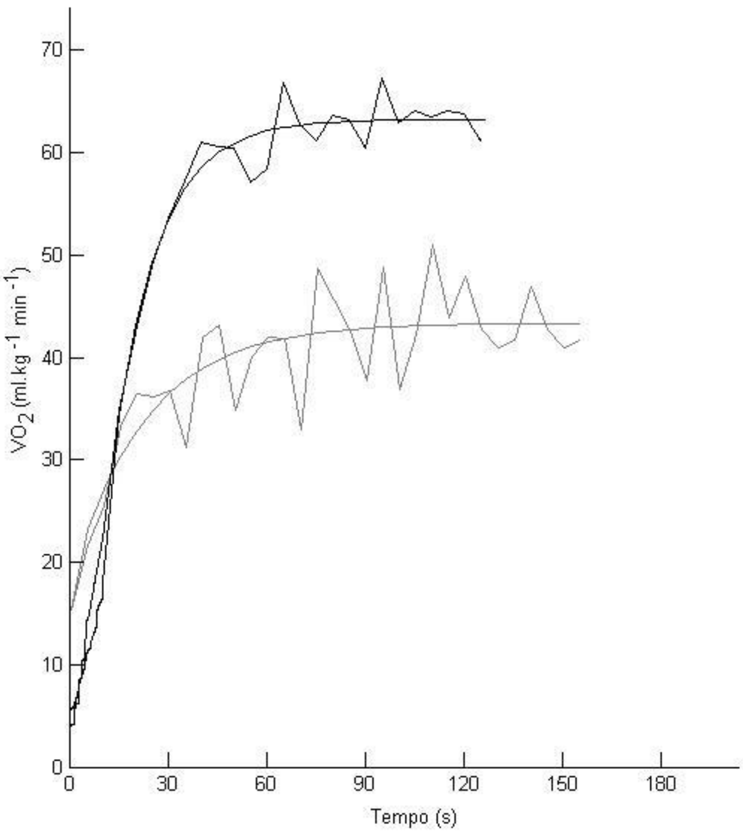

Figure 2. Example of two curve of the oxygen consumption kinetics corresponding to two distinct intensities – to the individual anaerobic threshold (grey color) and to the maximum velocity of 200 m *crawl* (black color).

The mean values (± sd) of A_{Ian}, A_{200}, t_{Ian}, t_{200}, TD_{Ian} and TD_{200}, at moderate and extreme intensities, are presented in table 2. Statistically significant differences were obtained in two kinetic parameters (amplitude and time constant) between the 200 m performed at the lan_{ind} and maximal velocity intensities. Additionally, negative correlations were found between TD_{lan} and t_{lan} ($r = -0.74$, $P = 0.01$, Figure 3). Nonetheless, further significant relations were not found in the remaining studied parameters.

Table 2. Individual and mean (± sd) values of A_{lan}, A_{200}, t_{lan}, t_{200}, TD_{lan} and TD_{200} corresponding to the threshold where lan_{ind} occurred in the incremental protocol and at 200 m performed at maximum velocity.

Swimmer	**A_{lan} (ml.kg^{-1}.min^{-1})**	**A_{200} (ml.kg^{-1}.min^{-1})**	**t_{lan} (s)**	**t_{200} (s)**	**TD_{lan} (s)**	**TD_{200} (s)**
#1	38.52	44.83	23.60	18.16	4.90	19.51
#2	31.05	32.03	19.17	22.32	9.99	15.00
#3	22.86	32.54	23.75	8,82	9.51	2.36
#4	26.73	33.57	8.85	9.33	4.99	9.99
#5	37.32	36.81	20.63	14.56	7.90	9.00
#6	18.57	45.18	23.49	22.41	17.37	4.32
#7	28.92	45.63	12.93	7.05	9.99	5.15
#8	34.52	40.72	7.79	11.01	25.0	4.98
#9	31.45	36.02	9.91	7.39	20.0	19.59
#10	22.94	36.97	20.24	11.14	13.99	4.81
Mean (±sd)	26.32 (±9.73)	38.43 (±5.30) *	18.89 (±6.53)	13.21 (±5.86) *	12.36 (±6.62)	9.47 (±6.42)

A_{lan}, A_{200} = amplitude of the 200 m at the intensity corresponding to lan_{ind} and maximum velocity, respectively; TD_{lan}, TD_{200} = time delay of the 200 m at intensity corresponding to lan_{ind} and maximum velocity, respectively; t_{lan}, t_{200} = time constant of the 200 m at intensity corresponding to lan_{ind} and maximum velocity, respectively. *Significantly different from the respective kinetic parameter corresponding to the intensity individual anaerobic threshold.

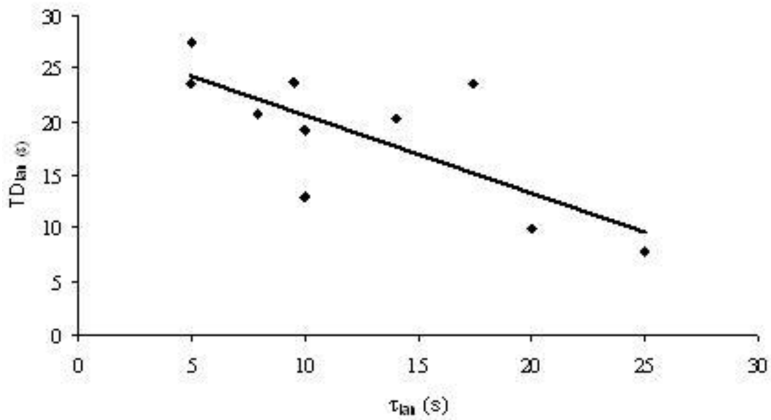

Figure 3. Ratio obtained between time of the beginning of the fast component to the intensity corresponding to the individual anaerobic threshold (TD_{lan}) and the time constant of the fast

component to the intensity corresponding to the individual anaerobic threshold (t_{Ian}) (y = 26.62 – 0.75x, n = 10, r = -0.74, $P \leq 0.05$).

Discussion

The aim of the present study was to assess and compare the VO_2 kinetics in 200 m *crawl* performed at two distinct swimming intensities: moderate (corresponding to the Ian_{ind}) and extreme (at maximal intensity). Since these two intensities are considered very important in the swimming training, as they are used for the development of the aerobic and anaerobic capacities, respectively, it seems crucial to provide better understanding on the VO_2 kinetic parameters. The literature has highlighted the study of low and moderate effort intensities, while studies concerning higher intensities are scarcer, which are representative of the swimming rhythm used during competition. Moreover, the existing studies occurred at unspecific and/or laboratory evaluation conditions (e.g. cycling ergometer and treadmills), compromising hence the validity and applicability of their results. Concerning swimming, only (Rodríguez et al., 2008; Rodríguez et al., 2003; Sousa et al., 2011) carried out studies at high intensities and at conditions as close as possible to the real swimming conditions, and there are no comparative studies between intensity domains.

Exercise intensity below the Ian_{ind} is characterized by the presence of three distinct phases: cardiodynamic, fast and the VO_2 stabilization which occurs three minutes after the beginning of the exercise (Xu & Rhodes, 1999). The intensity immediately above the Ian_{ind} presents an additional phase (slow component), which delays the onset in the VO_2 stabilization, appearing approximately 10 minutes after the beginning of the effort (Burnley & Jones, 2007). However, being the upper boundary of the moderate intensity and, consecutively, the lower one in the high intensity domain, the Ian_{ind} is an intensity little studied concerning the VO_2 kinetics. However, (Özyener et al., 2001) refer that moderate intensities are well-described by monoexponential fittings, instead of the high intensities (high and sever intensity domains) which are better characterized by bi-exponential fittings.

In the present study, and considering the F-Test values, it was verified that the intensity corresponding to the lan_{ind}, the VO_2 kinetics will be possibly described considering the existence of a single phase (fast component) and, consequently, the use of a bi-exponential fitting becomes unnecessary. Although no study has been carried out at this specific intensity, other ones conducted at the moderate intensity domain presented monoexponential fitting in the VO_2 kinetics (Carter et al., 2000; Carter et al., 2002; Cleuziou et al., 2004; Fawkner & Armstrong, 2003; Fawkner et al., 2002; Pringle et al., 2003). Concerning extreme intensity, monoexponential fittings were previously defined as being more positive for this intensity domain (Sousa et al., 2011).

Concerning the kinetic parameters, we verified that they are significantly different between the two exercise intensities studied, especially regarding amplitude and time constant. Thus, higher values of these two parameters were obtained in the 200 m *crawl* performed at maximal velocity, contrary to the time delay whose mean values were higher at the intensity corresponding to the lan_{ind}. The amplitude values corroborate the ones presented in the literature, either for the moderate (Barstow & Mole, 1991; Carter et al., 2002; Cleuziou et al., 2004; Pringle et al., 2003) or for the extreme domain (Sousa et al., 2011), where only the later was carried out with swimming. The tendency for higher values of amplitude in the extreme domain supports the literature carried out in cycle ergometer (Carter et al., 2002; Cleuziou et al., 2004; Pringle et al., 2003) and in domains of high intensity (Scheuermann & Barstow, 2003). These differences are due to the higher values of VO_2 reached in the extreme domain (higher oxygen demand), since as the effort intensity increases, the amplitude gain is higher. This fact is well explained in figure 2, where the higher VO_2 values reached at the end of the exercise can be observed.

Despite this, higher VO_2 values are also observed at the beginning of the moderate effort, comparatively to the effort performed at extreme intensity. Such fact is due to the previous performance of the 200 m *crawl* steps included in the protocol used (cf. instrument and procedures section) and that, despite being performed at low intensity, induced an increase in the VO_2 baseline values at the beginning of the following step. However, studies conducted refer that only previous exercise of high intensity conditions and influences the following efforts, namely slow component VO_2 (Koppo & Bouckaert, 2000a; Koppo & Bouckaert, 2000b) kinetics. Thus, it seems that the existence of low intensity plateaus preceding the effort corresponding to the lan_{ind} did not influence the respective VO_2 kinetics to lan_{ind}. Significant differences went to the time constant, being higher at the intensity corresponding to the lan_{ind}, clashing hence with some studies which refer the constancy of this parameter along the different intensities (Carter et al., 2000; Cleuziou et al., 2004; Pringle et al., 2003). However, it should be mentioned that the later ones were performed in cycle ergometer and comparing moderate to high intensity and/or severe domains.

In spite of this information, the values of the time constant observed for the m *crawl* performed at maximal velocity are lower than the ones reported in the literature (Rodríguez et al., 2008; Rodríguez et al., 2003), especially for the 100 and 400 m distances, but similar to the ones by Sousa et al. (2011) for the same distance. Regarding the intensity corresponding to the lan_{ind}, the values presented corroborate the ones reported in the literature for efforts performed in cycle ergometer (Carter et al., 2000; Carter et al., 2002; Cleuziou et al., 2004; Fawkner et al., 2002; Pringle et al., 2003). In the present study, the fact the time constant is not similar between the two intensities seems to be due to the extreme intensity at which the 200 m *crawl* were performed. Therefore, and since the value of the time constant describes the adaptation profile of the cardiovascular and muscular systems at the intensity of the performed effort (Markovitz et al., 2004), the sudden and exponential need of VO_2 to higher intensities (Figure 2) will be able to explain the lower values of this parameter.

The time delay was the only kinetic parameter where significant differences have not been verified between the two studied intensities, corroborating the studies which compare the moderate and high exercise domains (Carter et al., 2002) and moderate and severe domains (Cleuziou et al., 2004). However, Pringle et al. (2003) showed that this parameter ranges between the moderate, high and severe domains. Although the mean values found in our study are lower than the ones found in the literature for the moderate domain (Carter et al., 2000; Cleuziou et al., 2004; Pringle et al., 2003), the values corresponding to the extreme domain agree with the only study conducted in the swimming environment for the 200 m distance (Sousa et al., 2011). In the moderate domain, the differences found may be due to the fact the studies mentioned have been conducted in different sports modalities.

The negative correlation observed between the delay and time constant in the 200 m *crawl* performed at lan_{ind} intensities has not been previously reported in the literature; nevertheless, in the present sample the swimmers, whose fast component of VO_2 started earlier (shorter time delay), were those who also needed more time (longer time constant) until they reached stabilization in the VO_2 consumption. Thus, the sports performance level of our sample (high level) as well as its specialty (sprinters) seem to be two factors which explain the correlations reported here.

Conclusion

Both were well described by mono exponential fittings and significant differences have been verified between them concerning amplitude and time constant. Thus, higher values of these two kinetic parameters have been obtained in 200 m *crawl* performed at maximum velocity, contrary to the timed delay whose mean was higher at the intensity corresponding to the lan_{ind}. Additionally, negative correlations have been obtained between TD_{lan} and t_{lan}.

Acknowledgments

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Appendix V

VO_2 slow component assessment along an incremental swimming protocol.

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Abstract

The present study analysed the oxygen uptake slow component (VO_{2SC}) of front crawl swimming along an incremental swimming protocol, using a multi-exponential function. Eleven well-trained swimmers (20.4±2.5 yrs, 1.80±0.06 m and 74.1±4.12 kg) performed a front crawl incremental protocol of 7x300 m until exhaustion (with increments of 0.05 $m \cdot s^{-1}$ and 30 s intervals between steps). VO_2 was collected breath by breath using a portable gas analyzer (K4b2) connected to the new AquaTrainer respiratory snorkel (both from Cosmed, Italy). VO_{2SC} was assessed using a double exponential regression model with exponential terms amplitudes, time delays and time constants representing the VO_2 kinetics fast (1) and slow (2) components. In addition, the calculation of the VO_{2SC} values through the fixed interval method was also conducted by subtracting the average VO_2 observed in the last 40s of each step by the average VO_2 observed in the 3rd min of exercise. A paired T-test was used to compare both methods along the incremental test ($P \leq 0.05$). The multi-exponential model showed that the VO_2SC was above 200 $ml \cdot min^{-1}$ from the 5th until the 7th step of the incremental protocol, i.e., intensities above the anaerobic threshold. Differences were observed in mean values of VO_2SC obtained by the mathematical modelling and the fixed interval method in every step of the protocol ($P \leq 0.05$, $d > 0.76$). It was concluded that in well-trained front crawl swimmers VO_2SC exists in a significant faction at exercise intensities above the anaerobic threshold. This means that at heavy and severe swimming intensities (i.e., above the anaerobic threshold and above the velocity that elicits the VO_2max, respectively) the higher work rates implied the recruitment of faster but easily fatigable fibers, which could lead to less efficient processes, and consequently, to higher VO_2SC mean values.

Key words: oxygen uptake, slow component, models, incremental swimming

Introduction

The magnitude and nature of the adjustment of the oxygen uptake (VO_2) kinetics in a step workload has three components: (i) the first phase, the cardio-dynamic component, corresponds to a fast increase in alveolar VO_2, allowing a transient plateau of 15-20 s after on-transition (Hughson et al., 1988); (ii) the second phase, or fast component, is linked to muscular VO_2 (Mole & Hoffmann, 1999), which increases exponentially up to an alleged steady-state, taking about 2-3 min on healthy subjects (Burnley et al., 2002); and (iii) the third phase, depending on the exercise intensity, could evidence a VO_2 plateau or (if exercising above the anaerobic threshold) a slow component (VO_2SC), expressing the raising of VO_2 above the predicted demand (Burnley & Jones, 2007).

The VO_2SC has been traditionally assessed by the fixed intervals method (Phillips et al. 1995), i.e., by the differences of minute average VO_2, particularly between the last and the 3rd min (Mole & Hoffman, 1999) or the 2nd min of exercise (Koppo & Bouckaert, 2002). Agreeing that this method is prone to error (Mole & Hoffman, 1999), the VO_2SC has alternatively been assessed by mathematical modelling, as the amplitude of an exponential function (Barstow & Mole, 1991).

In swimming, the studies addressing the VO_2 kinetics and the VO_2SC are scarce and recent, appearing only when portable telemetric metabolic measurement carts began to be available for aquatic environment research. The pioneer studies on the topic presented some limitations, once the VO_2SC was assessed using fixed intervals methods, a simple methodology that does not yield reliable data (especially when evaluating elite swimmers), tending to underestimate the VO_2SC values (e.g. Fernandes et al., 2003). Moreover, some of these studies were performed in swimming flume (not in ecological swimming conditions; Demarie et al., 2001). In addition, it was demonstrated in running (Reis et al., 2007) and cycling exercise (Billat et al., 1998) that the VO_2SC is sensible to the rate of blood lactate accumulation and that the exercise intensity immediately above the anaerobic threshold generally marks the appearance of the VO_2SC

phenomenon. However, this is very scarcely identified in swimming, especially during a front crawl incremental protocol, which is frequently used for evaluating swimmers and to control the training process (Pyne et al., 2001; Fernandes et al., 2006).

As findings about VO_2SC during incremental swimming could be of great interest and application for the training process, the present study aimed to analyse the VO_2SC phenomenon across low to severe swimming intensities, using a mathematical approach. It was hypothesised that the VO_2SC would appear at steps above the anaerobic threshold (i.e., at the heavy intensity) and at steps above the velocity that elicits VO_2max (i.e., severe intensity), but not bellow and at the anaerobic threshold (i.e., at low to moderate intensities). Complementarily, a comparison between the multi exponential function with a fixed interval method was carried on.

Methods

Participants

Eleven middle and long distance front crawl swimmers (20.4±2.5 yrs, 1.80±0.06 m, 74.1±4.12 kg and 248 ± 3.10 s of their best performance in the 400 m front crawl in 25 m pool)) voluntary participated in the present study. Participants were completely informed about the procedures and demands of the study and signed a written informed consent approved by the Institutional Ethics Committee.

Procedures

The experimental moments took place in a 25 m indoor swimming pool (1.90 m deep) with (mean ± SD) 27.3 ± 0.1 ^{o}C water temperature, 28.5 ± 0.2 ^{o}C room temperature and 55.2 ± 0.4% humidity from 8:00 until 12:00 am. After a 20 min duration moderate intensity warm-up, swimmers performed a front crawl intermittent incremental protocol specific for maximal VO_2 assessment (VO_2max), consisting of 7x300 m front crawl, with increments of 0.05 $m{\cdot}s^{-1}$ and 30 s resting intervals, until voluntary exhaustion (Fernandes et al., 2011). The speed of the last step was established according to each swimmer's 400 m front crawl time at the moment of the experiments, with successive 0.05 $m{\cdot}s^{-1}$ being subtracted allowing the determination of the mean target speed for each step. A visual pacer with flashing lights on the bottom of the pool (GBK-Pacer, GBK electronics, Aveiro, Portugal) was used to help maintaining the pre-defined individualized paces. In-water starts and open turns were performed due to the constraints of the ventilatory evaluation.

Assessment of gas pulmonary exchange

Respiratory gas exchange during the incremental protocol was assessed breath-by-breath with a portable gas analyser (Cosmed K4b2, Cosmed, Italy) connected to recently developed snorkel and valve system (Aquatrainer, Cosmed, Italy; Baldari et al., 2013). The K4b2 apparatus was calibrated following a standard certified commercial gas preparation (cf. K4b2 user manual) and measured the atmospheric pressure and ambient temperature (with the relative humidity being manually reported before each test). In addition, the temperature of the expired gas detected at the turbine was at measured the end of each 300 m step with an infrared thermometer (Kramer, Med.Ico).

Assessment of blood lactate concentrations

Capillary blood samples (25 µl) for blood lactate concentration ($[La^-]$) analysis were collected from the ear lobe at the resting period, immediately after the end of each step, and at 3 and 5 min during the recovery period (Lactate Pro, Arkay, Inc, Koyoto Japan).

Data analysis

Prior the VO_2 kinetics modelling, the breath-by-breath collected data were edited to exclude occasional errant breaths caused by swallowing, coughing, sighing or signal interruption and so forth (cf. Fernandes et al., 2012) that typically arise due to some constraints caused by the respiratory snorkel and valve system and by swimming proper characteristics (eg. long apnea moments during the turns). In addition, values greater and lower than ± 4 SD from the local mean were omitted (Özyener et al., 2001). To ensure a true VO_2 steady state, the breath-by-breath data were smoothed at 3 breaths and averaged at 5 s using the time-averaging function of the Cosmed analysis software.

The kinetics of VO_2 was modelled by the following exponential function:

$$VO_2(t) = VO_{2b} + A_1 * (1 - e^{-(t - TD_1/\tau_1)}) + A_2 * (1 - e^{-(t - TD_2/\tau_2)}) \quad \textbf{(1)}$$

Where *t* is the time (s), V_b is the VO_2 at the beginning of the exercise ($ml \cdot min^{-1}$), A1 and A2 are the amplitude of the fast and slow components ($ml \cdot min^{-1}$), TD_1 and TD_2 are the times of the beginning of the fast and slow components (s) and t_1 and t_2 are the time constants of the fast and slow components (s), respectively. A non-linear regression was applied to fit the time responses of VO_2, using the least square method to obtain the corresponding coefficients (the VO_2SC amplitude is given by the magnitude of the second exponential). The calculation of the VO_2SC through the fixed interval method was made by subtracting the average VO_2 observed in the last 40 s of each step of the protocol by the average VO_2 observed in the 3rd min of exercise. All mathematical and modelling procedures were done using the MATLAB R2010b (Mathworks, USA). The individual anaerobic threshold was determined by the $[La^-]$/velocity curve modelling method (also using the least square method; Fernandes et al., 2011), being possible to determine the exact point for the beginning of an $[La^-]$ exponential rise and, therefore, the corresponding step of the incremental protocol.

Statistical analysis

The mean values ± SD for the descriptive analysis were obtained for all the variables of the study and normality of distribution was verified through the Shapiro Wilk-test. The T-test for repeated measures was used for the inferential statistics and significant level was established at 0.05. It was considered a

(Cohen, 1988): (i) small effect size if 0 ≤ |d| ≤ 0.2; (ii) medium effect size if 0.2 ≤ |d| ≤ 0.5; and (iii) large effect size if |d| > 0.5.

Results

Figure 1 shows the VO_2 kinetics of a representative swimmer in the 5, 6 and 7th steps of the intermittent incremental protocol, being evident the appearance of the VO_2SC superimposed on the primary component.

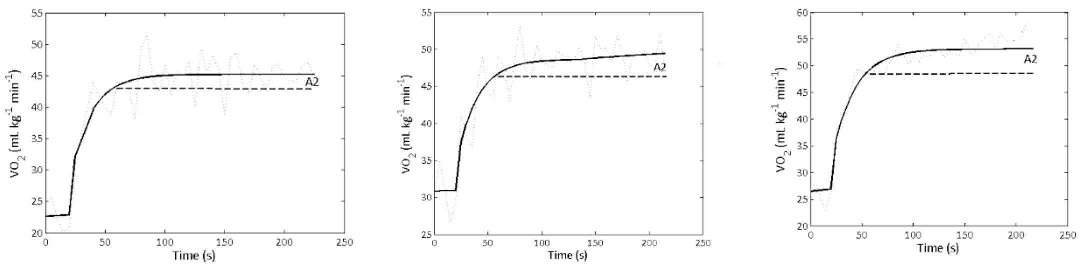

Figure 1. Oxygen uptake kinetics in the 5th, 6th and 7th steps of the incremental protocol in a representative swimmer, being indentified the amplitude of VO_2 slow component (A2) by a black dotted line.

Complementarily, Table 1 shows the mean ± SD values for the VO_2SC and other related parameters (obtained through mathematical modelling and from rigid interval methods) in the seven steps of the front crawl incremental intermittent protocol ([La^-] values were also presented). The most relevant finding was the significant VO_2SC values found in the three last steps of the protocol (from the 5th until the 7th step), i.e., at intensities higher than the anaerobic threshold (that occurred, generally, at the 4th step). In addition, it was observed that VO_2SC mean values were higher using the mathematical modelling compared with the fixed interval method in each step of the incremental protocol ($P < 0.05$; $d > 0.76$).

Table 1. Mean ± SD values of the VO_2 kinetics parameters extracted from the multi-exponential model and rigid interval method in each step of the incremental protocol. Blood lactate concentrations were also displayed.

	1st step	2nd step	3rd step	4th step	5th step	6th step	7th step
A1 ($ml.min^{-1}$)	1874.7±251	1941.4±311	2185.9±207	2260.1±244	2445.3±229	2749.1±385	3082.5±445
A2 ($ml.min^{-1}$)	4.4±7.4	9.93±17.8	11.8±22.3	99.2±66.6	**234.9 ±29.6***	**274.17±103.7***	**400.8±1.7***
TD1 (s)	13.4±4.3	15.6±4.6	17.3±5.4	12.9±5.3	14.2±5.2	13.1±4.1	12.1±4.2
τ1 (s)	25.6±8.0	25.9±5.4	26.2±5.9	30.0±9.9	24.8±8.4	22.3±8.3	22.3±16.1
TD2 (s)	146±49.1	175±22.6	151±40.5	176±34.1	169±37.3	168±34.2	157±32.7
τ2 (s)	274±37.4	280±14.2	268±48.5	266±54.1	274±33.6	262±43.6	210±47.1
ΔVO_{2SC} ($ml.min^{-1}$)	2.8±9.2	6.4±13.1	13.3±6.2	94.1±49.9	**205.1±13.3**	**239±32.9**	**301±77.1**
[La^-] ($mmol.l^{-1}$)	1.15±0.4	1.83±1.22	2.23±1.41	2.56±1.62	3.12±1.31	7.13±1.14	8.41±1.54

A1: amplitude of the 1st exponential (fast component); A2: amplitude of the 2nd exponential (slow component, given by the mathematical modelling); τ1 and τ2: time constant of the equation for the 1st and 2nd exponentials, respectively; TD1 and TD2 time delay of the 1st and 2nd exponentials, respectively; ΔVO_{2SC}: slow component given by the fixed interval method, subtracting the average VO_2 observed in the last 40 s of each step of the protocol by the average VO_2 observed in the 3rd min of exercise; [La^-]: blood lactate concentrations. *Differences between the slow component determined by the mathematical modelling and slow component determined by the fixed interval method; $P < 0.05$.

Discussion

The aim of this study was to analyse the VO_2SC values of well-trained swimmers when performing an incremental protocol from low to severe front crawl swimming intensities. A comparison between mathematical and fixed interval methods for VO_2SC assessment was also accomplished. We hypothesised that VO_2SC would appear at swimming intensities above the individual anaerobic threshold, i.e., at the heavy and severe intensity domains. The experience was conducted in ecological swimming pool conditions, using a recently developed and comfortable snorkel and valve system specific for breath-by-breath analysis (Baldari et al., 2013). The main finding of the current study was that, independently of the methodology of assessment used, the VO_2SC was evident and had physiological meaning at swimming intensities above the one corresponding to the anaerobic threshold, confirming the initial hypothesis.

Traditionally, the VO_2 kinetics response to exercise has been studied at three intensity domains: moderate - below the anaerobic threshold, heavy - above the anaerobic threshold and below the critical power and severe - above the critical power until the VO_2max boundary (Burnley & Jones, 2007). At intensities above the anaerobic threshold, the VO_2 steady state is delayed due to the existence of a VO_2SC (Jones & Burnley, 2009). In the current study, at intensities above the anaerobic threshold (at the heavy and severe intensity domains), the VO_2SC phenomenon was observed (physiological meaning, ≥200 $ml.min^{-1}$), which corroborates the swimming literature where the VO_2SC has been reported at intensities higher than the anaerobic threshold (Demarie et al., 2001; Fernandes et al., 2008; Sousa et al., 2011), although this phenomenon was not yet investigated in an entire incremental protocol using mathematical modelling. The reason for the existence of a VO_2 slow component is still a matter of debate, but it has been suggested that it is influenced by muscle perfusion pressure and O_2 availability (Jones & Poole, 2005). In the current study, the use of an incremental protocol that comprises low to severe swimming intensities, reflecting in a progressive increase of the [La^-] values, could explain the significant VO_2SC values observed.

Although the VO_2SC phenomenon was observed using both assessment methodologies, the mathematical modelling method evidenced higher VO_2SC values comparing to the rigid interval, which is in agreement with Reis et al. (2013) for submaximal swimming intensities. In fact, Jones & Poole (2005) stated that the later method is a a simple rough estimate of the VO_2 slow component. Moreover, when applying the mathematical modelling to front crawl swimming at the intensity corresponding to maximal oxygen uptake, Fernandes et al. (2008) showed a VO_{2SC} of 365.27 $ml \cdot min^{-1}$, a value near that obtained in the current study for the step where the VO_2max occurred (the last one). In addition, our results obtained with the fixed interval method were similar to previous studies conducted with the same methodological approach (Demarie et al., 2001; Fernandes et al., 2003).

It seems also important to underline that the values of [La^-] corresponding to the anaerobic threshold where lower than the average value of 4 $mmol.l^{-1}$ traditionally used for aerobic capacity training control and training prescription. This evidences the importance of using individualized methodologies for the characterization of this boundary, in line with the suggestions of Stegman et al. (1981) and our own data (e.g. Fernandes et al., 2010; Fernandes et al., 2011; Figueiredo et al., 2013). The [La^-] values in the final of incremental protocols that aims to assess maximal VO_2 values is normally around to 8 $mmol.l^{-1}$ (Fernandes et al., 2008; Ogita et al., 1992) what was observed in the current study.

Conclusion

Our results indicated that well trained front crawl swimmers have an evident VO_2SC at exercise intensities above the anaerobic threshold. This means that at heavy and severe swimming intensities, the higher work rates leaded to the recruitment of faster but highly fatigable fibers (type IIa and b), which could lead to less efficient metabolic processes, and consequently to higher VO_2SC mean values. Our results indicated also that mathematical modelling of the VO_2 kinetics along an incremental swimming test provide higher VO_2SC as compared to fixed interval methods nonetheless that both methodologies evidences VO_2SC values above the typical threshold reported as having a physiological meaning ($\geq$200 ml.min^{-1}). So, the VO_2SC should be well considered when performing at intensities above the anaerobic threshold even if the exercise durations are not too long (as 300 m steps).

Acknowledgments

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Appendix VI

Biomechanical determinants of force production in front crawl swimming.

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Abstract

Swimming propulsive force is a main performance determinant that has been related to some biomechanical parameters. Nevertheless, as the link among those parameters and force production remains unclear, it was aimed to examine the relationships between the stroking parameters, intracycle velocity variations, arm coordination, propelling efficiency and force production in front crawl swimming. Ten trained swimmers performed two repetitions of an intermittent graded velocity protocol using arms-only front crawl technique (one on the system to measure active drag force, which gives us the mean propulsive force, and other in free-swimming conditions), consisting in 10 bouts of 25 m from slow to maximal velocity. The tests were videotaped in the sagittal plane (2D kinematical analysis) and video images were digitized enabling the stroking parameters (velocity, stroke frequency and stroke length), intracycle velocity variations, index of coordination and propelling efficiency assessment. Force presented a direct relationship with velocity, stroke frequency and index of coordination (r = 0.86, 0.82, 0.61, respectively, $P < 0.05$) and an inverse relationship with stroke length, intracyclic velocity variations and propelling efficiency (r = -0.66, -0.57, 0.60, respectively, $P < 0.05$). The relationships between force and velocity, and between force and intracyclic velocity variations, were best expressed by a power regression model ($F = 18.01v^{2.5}$ and $F = 3.00IVV^{-1.50}$, respectively). A quadratic regression was the most appropriated model for expressing the relationships between force and stroke frequency ($F = -57.10SF^2+220.98SF-105.04$), index of coordination ($F = 45.45IdC^2+2.10IdC+0.05$) and propelling efficiency ($F = 328.62\eta_F^2-1350.212\eta_F+1536.46$). High stroke frequency, optimal coordination and low intracyclic velocity variations seem to be required to produce high force values in front crawl swimming. By knowing how to manipulate those variables, both in training and competition conditions, swimmers would be able to increase their force production.

Key words: biomechanics, force, motor control, velocity, swimming

Introduction

Swimming velocity depends on the generation of propulsive force necessary to match the hydrodynamic drag produced by the moving body. So, the capability to produce high propulsive force, while reducing the opposite drag, is decisive to achieve a certain velocity (Barbosa et al., 2010; Toussaint et al., 1988). Since velocity is a product of stroke frequency (SF) and stroke length (SL), and its increase (or decrease) is determined by SF and SL combinations,[3,4] the relationship between these parameters is one of the major points of interest in swimming training and research (Barbosa et al., 2010; Fernandes et al., 2005). Nevertheless, the complex relationships between those stroke characteristics have been often reported as the swimmers' ability to swim with high efficiency, emphasizing the swimming technique rather than the propulsive force production. In fact, the relationship between stroking parameters and the effective ability to produce muscular force (to execute the stroke cycles) lacks experimental evidence.

The action of the arms, legs and trunk varies, during a stroke cycle, resulting in an intermittent application of force and, therefore, in intracycle velocity variations (IVV) (D' Acquisto & Costill, 1998) that are responsible for average velocity degradation (Figueiredo et al., 21012). The IVV have also been reported as a relevant swimming performance determinant since, for a finite energy supply, the best solution to optimize performance is to reduce its magnitude and increase the capacity to produce propulsive force (Figueiredo et al., 2013b). Increases in IVV imply greater mechanical work demand and, theoretically, changes of 10% in the swimming velocity within a stroke cycle results in an additional work of about 3% (Nigg, 1983). Therefore, IVV should give an indication of swimming efficiency and swimmer's technical level (Seifert et al., 2010).

Complementarily, it is known that IVV are influenced by inter-arm coordination (Seifert et al., 2010; Schnitzler et al., 2009) (traditionally assessed by the index of coordination - IdC - that quantifies the lag time between the propulsive action of the two arms). It was observed previously that when during increasing swim paces a change from catch-up to superposition has been adopted by elite swimmers to maintain continuity between the propulsive phases (Seifert et al., 2010), meaning that using a best coordination solution, swimmers should be able to reduce IVV and optimize propulsion (Figueiredo et al., 21012; Figueiredo et al., 2013b).

Nonetheless, the propulsion continuity in swimming could not be automatically related to greater propulsion generation, since it depends on the correct orientation and velocity of the body segments. Thus, the capability to generate effective propulsion reflects the swimmers' propelling efficiency, and despite it has been considered as a swimming performance determinant, and discriminative of technical level (Toussaint et al., 1990), its relationship with force production has not yet been clarified. The purpose of this study was to examine the relationships between stroking parameters, IVV, arm coordination, propelling efficiency and force production in front crawl swimming.

Material and Methods

Participants

Ten trained male swimmers volunteered to participate in the present study. Their main physical characteristics, training background and performance are as follows: 18.96 ± 2.56 years, height: 1.80 ± 0.65 m, body mass: 72.46 ± 4.33 kg, years of training background: 13.57 ± 3.08, percentage of the 100 m world record: 89.57 ± 15.91%). Participants were previously familiarized with the test procedures and the equipment used in the experiment. All participants provided informed written consent before data collection, which was approved by the local ethics committee. All experiments were conducted according to the Declaration of Helsinki.

Experimental procedure

The test session took place in a 25 m indoor pool, 1.90 m deep, with a water temperature of 27.5ºC. A warm-up of low to moderate swimming intensity was conducted, both in free swimming and on a system to measure active drag force (MAD-system) (Toussaint et al., 1990). Briefly, each subject performed two sets of an intermittent graded velocity protocol consisting in 10 bouts of 25 m front crawl using only the arms (with the legs elevated and constrained by a pull buoy), with 3 min rest in-between, from slow to maximal velocity: one set was conducted on the MAD-system and the other in free-swimming conditions, with a 24 h interval. Each bout was self-paced to avoid the velocity variations that can arise when the swimmer follows a target (Seifert et al., 2010). The swimmers were randomly assigned to start the testing by performing on the MAD-system or swimming freely. Each subject swam alone, avoiding pacing or drafting effects.

MAD-system

The MAD-system required the swimmer to directly push-off fixed pads attached to a 23 m rod, which was fixed 0.8 m below water surface, and had a standard distance of 1.35 m between each pad (Figure1, left panel). The rod was instrumented with a force transducer allowing measurement of push-off force from each pad (Figure 1, right panel).

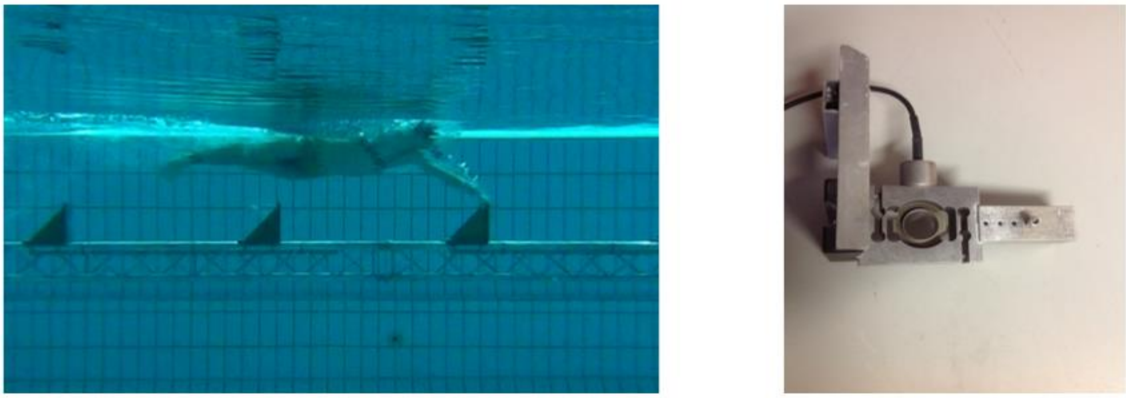

Figure 1. System to measure active drag (MAD-sytem, left panel) and respective force transducer (right panel).

The force signal were acquired by an A/D converter (BIOPAC Systems, Inc., Goleta, CA, USA) at a sample rate of 500 Hz and filtered with a low pass digital filter with a cut-off frequency of 10 Hz. Assuming a constant swimming velocity, the mean force equals the mean drag force and, hence, the 10 velocity/force ratio data were least square fitted according to Equation 1:

$$D = A.v^{n} \quad \textbf{(1)}$$

where D is active drag force, A and n are parameters of the power function and v is the swimming velocity. For each subject A and n were estimated using equation (1) (Matlab version R2012a, Mathworks, Inc., Natick, MA, USA) with a Levenberg-Marquardt algorithm (Toussaint et al., 1988; Toussaint et al., 2004).

Biomechanical parameters

Swimmers were videotaped in the sagittal plane (for 2D kinematical analysis) using a underwater camera (Sony® DCR-HC42E, 1/250 digital shutter, Nagoya, Japan) kept at 0.30 m depth (Sony® SPK-HCB waterproof box, Tokyo, Japan) and at 6.78 m from the plane of movement, as previously described (Fernandes et al., 2012). Subjects were monitored when passing through a specific pre-calibrated space using two-dimensional rigid calibration structure (6.30 m^2) with six control points. The video images were digitized using Ariel Performance Analysis System (Ariel Dynamics, San Diego, USA) at a frequency of 50 Hz, considering five anatomical reference points: humeral heads, ulnohumeral joints, radiocarpal joints, 3rd dactylions and trochanter major. A 2D reconstruction was accomplished using Direct Linear Transformation algorithm and a low pass digital filter of 5Hz.

SF was assessed by the inverse of the time needed to complete one stroke cycle and SL by the horizontal displacement of the left hip. The mean velocity was computed by dividing the swimmer’s average hip horizontal displacement by the time required to complete one stroke cycle. The IVV was calculated through the coefficient of variation of the velocity to time mean values (Equation 2) (Figueiredo et al., 2012):

$$CV = SD.mean^{-1} \tag{2}$$

where CV is the coefficient of variation and SD the standard deviation of velocity values.

Arm coordination was quantified using the IdC, measuring the time duration between the final of the propulsive action of one arm and the beginning of the propulsion of the other, and expressed as percentage of the overall duration of the stroke cycle (Chollet et al., 2000). The propulsive phase was considered to begin with the start of the backward movement of the hand until the moment where it exits from the water (pull and push phases), and the non-propulsive phase initiates with the hand water release and ends at the beginning of the propulsive phase (recovery, entry and catch phases). For the front crawl technique, three coordination modes were proposed (Chollet et al., 2000): (I catch-up, when a lag time occurred between the propulsive phases of the two arms (index of coordination < 0%); (ii) opposition, when the propulsive phase of one arm started when the other arm ended its propulsive phase (index of coordination = 0%) and (iii) superposition, when the propulsive phases of the two arms are overlapped (index of coordination > 0%).

The propelling efficiency (η_F) of the arm stroke was estimated by assessing the underwater phase only, according to Equation 3 (Zamparo et al., 2005):

$$nf = (v / 2.\pi.SF.L).(2/\pi) \tag{3}$$

being v the mean velocity of the swimmer, SF the stroke frequency (in Hz) and L the average shoulder to hand distance (assessed trigonometrically by measuring the upper limb length and the average elbow angle during the insweep of the arm pull). The equation was not adapted for the contribution of the legs (as originally proposed) as swimmers performed with arms only.

Statistical analysis

The normality of distribution was checked using the Shapiro-Wilk test. Descriptive statistics (mean, range and standard deviation) from all measured variables were calculated. A two-way ANOVA was used to compare the normalized velocity and SF in free swimming and MAD-system conditions, and the effect of bouts of 25 m on the different variables was analysed through the one-way ANOVA repeated measures. The relationships among variables were assessed by Pearson's correlation test and regression analysis (using second degree polynomial, linear, exponential, power or logarithm regression models). For the exponential and power regressions the coordination data were normalized between 0 and 1, as follows (Equation 4):

$$1-[(30-IdC)/60] \qquad \textbf{(4)}$$

Then, the model was created by averaging the individual coefficients and the regression model was selected in function of the error of each individual and the average equation. These statistical analyses were performed using IBM® SPSS Statistics and the level of significance was set at 5%.

Results

A non-significant difference (3.42 ± 0.93%) was observed for normalized velocity between free and MAD-system conditions, while a statistical difference of 19.57 ± 5.78% ($F_{8.162}$ = 380.76, P < 0.05) was noted between normalized SF (Figure 2).

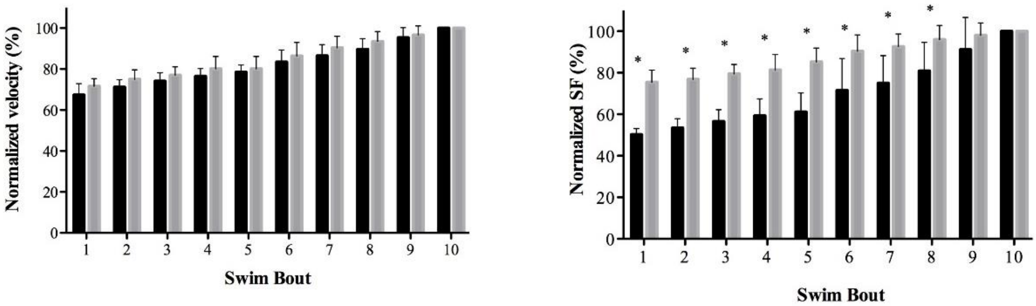

Figure 2. Comparison between free swimming (black) and MAD-system (gray) conditions for the normalized velocity (left panel) and the normalized stroke frequency (SF, right panel) at each velocity. * Significant difference between the two conditions, P<0.05.

For the 10 bouts of free swimming, the ANOVA indicated an increase of velocity ($F_{9.81}$ = 80.56, P < 0.05), SF ($F_{9.81}$ = 30.20, P < 0.05), IdC ($F_{9.81}$ = 9.64, P < 0.05) and force ($F_{9.81}$ = 50.27, P < 0.05), and decrease of SL ($F_{9.81}$ = 17.55, P < 0.05), IVV ($F_{9.81}$ = 4.14, P < 0.05) and η_F ($F_{9.81}$ = 11.94, P < 0.05). The results of the Person's correlation, among all variable, are presented in Table 1.

Table 1. Correlations coefficients among the studied variables. Significant correlation (r) at P<0.05.

	Velocity	**SR**	**SL**	**IVV**	**IdC**	**η_F**
Force	0.86	0.82	-0.66	-0.57	0.61	-0.60
Velocity		0.84	-0.57	-0.62	0.56	-0.48
SR			-0.84	-0.57	0.71	-0.77
SL				0.50	-0.69	0.86
IVV					-0.48	0.46
IdC						-0.74

SR= Stroke Frequency; SL= Stroke Length; IVV= Intracyclic velocity variations; IdC= Index of coordination; η_F = propelling efficiency

As the swimmers increased force production, the velocity (r = 0.86, P < 0.05), SF (r = 0.82, P < 0.05) and IdC (r = 0.61, P < 0.05) increased, and SL (r = -0.66, P < 0.05), IVV (r =-0.57, P < 0.05) and η_F (r = -0.60, P < 0.05) decreased.

From the five tested regressions models, two were found as the most appropriated, both for individual (Table 2) and polled analysis (Figure 3). The relationship between force and velocity and IVV showed that a power regression was the most appropriate fit and, on the other hand, a quadratic regression was found as the best model between force and SF, SL, IdC and η_F.

Table 2. Regression modelling between force (F) and velocity (v), stroke frequency (SF), stroke length (SL), intracyclic velocity variations (IVV), index of coordination (IdC) and propelling efficiency (η_F).

Regression	Equation	Mean Error	SD Error	Min<Error<Max	Min<R^2<Max	Mean R^2
Power	$F=18.01v^{2.5}$	0.09	0.03	0.01<Error<1.04	0.98<R^2<1	0.99
Quadratic	$F=-57.10SF^2+220.98SF-105.04$	0.23	0.19	0.01<Error<1.87	0.83<R^2<0.97	0.94
Quadratic	$F=338.62SL^2-250.55SL+51.18$	0.32	0.23	0.02<Error<1.98	0.78<R^2<0.92	0.87
Power	$F=3.00IVV^{-1.50}$	0.34	0.26	0.09<Error<2.11	0.43<R^2<0.90	0.63
Quadratic	$F=45.45IdC^2+2.10IdC+0.05$	0.21	0.19	0.05<Error<1.78	0.45<R^2<0.95	0.71
Quadratic	$F=328.62\eta_F{}^2-1350.212\eta_F+1536.46$	0.20	0.17	0.03<Error<1.55	0.68<R^2<0.96	0.81

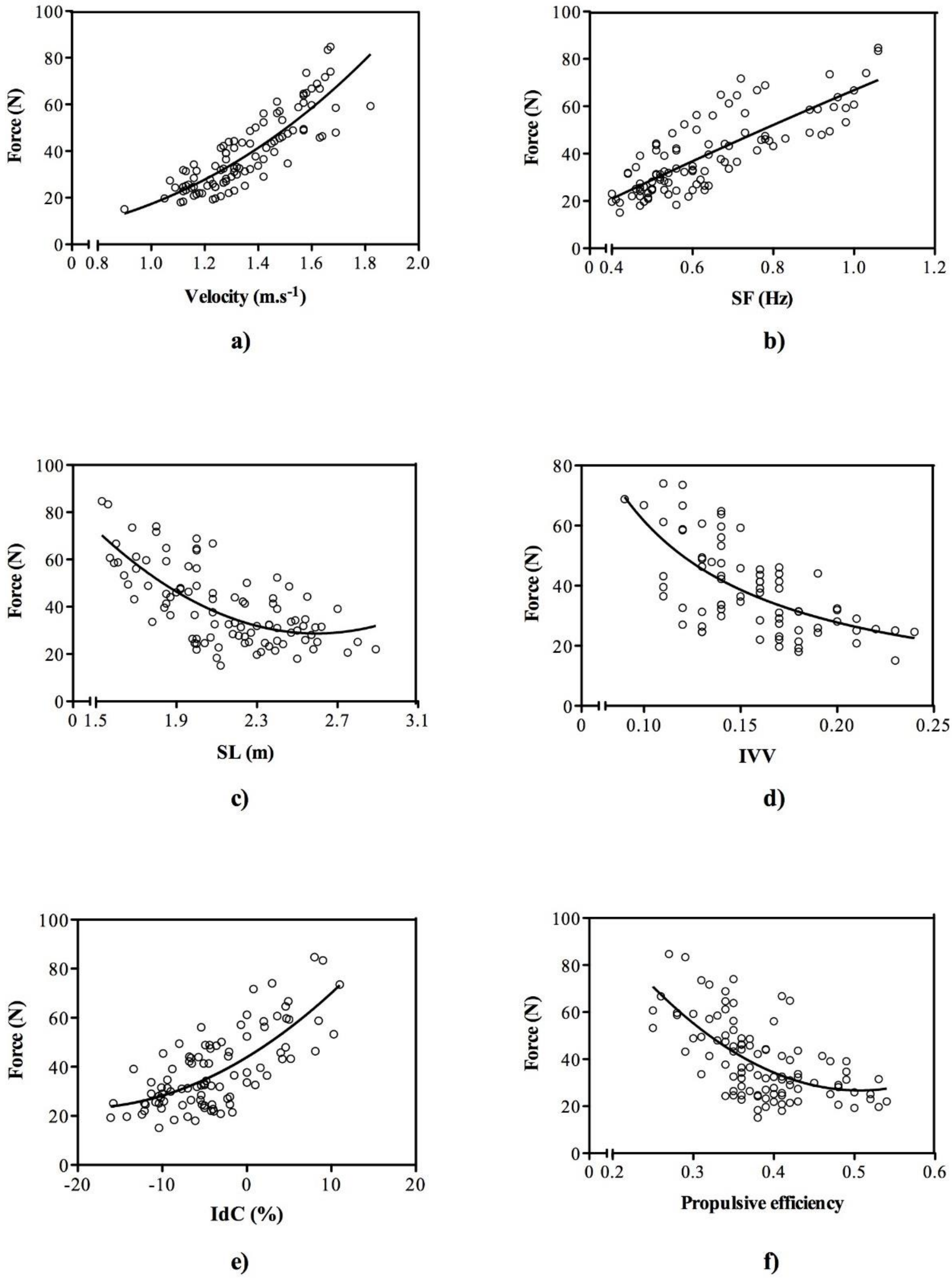

Figure 3. Relationship between force and velocity (a), stroke frequency (b) stroke length (c), intracyclic velocity variations (d), index of coordination (e) and propelling efficiency (f) average for the ten swimmers.

Discussion

Force production in front crawl swimming has been considered as a main performance determinant, but its relationship with the most relevant biomechanical parameters lacks experimental evidence. The aim of the present study was to examine the relationships between force and stroking parameters (velocity, SF and SL), IVV, IdC and η_F, in front crawl swimming. The main findings of the present study were that high force production requires increases in SF and, consequently, in velocity. Coordination adaptations permitted high force outputs due to continuity of propulsive phases and, concomitantly, IVV decreases, avoiding velocity degradation. The linkage between force and SF, SL, IdC and η_F showed a quadratic dependence and a power regression model was found between force and velocity and IVV.

In the present study, the assessed mean values of propulsive forces were assumed to be equal to the mean drag forces obtained from measurements on MAD-system (Berger et al., 1999), once, for a constant velocity the mean propulsive force should be equal to the mean drag force acting on the body of the swimmer (Toussaint et al., 1988; Toussaint et al., 2004). In addition, the maximal force production in free swimming would be similar to the recorded force production when swimming on the MAD-system, a fact that was confirmed by the normalized velocity. Nevertheless, the normalized SF changed between the two conditions, being higher on the MAD-system due to the fixed SL, as previously described (Seifert et al., 2010).

Concerning the stroking parameters, the correlation between force and velocity was positive and a quadratic dependence was observed. These data are in agreement with the literature (Martin et al., 1981; Toussaint et al., 1988; Toussaint et al., 2004), evidencing the importance of swimming velocity on force production, particularly with increasing velocity. Moreover, force produced by the swimmers showed to be positively influenced by SF increases, confirming previous investigations (Cabri et al., 1988; Martin et al., 1981) and consequently, lower SL (Barbosa et al., 2010). The quadratic linkage between force and these variables could be explained by the fact that, at early protocol stages (lower values of velocity), force production might mostly be due to the fast increase in SF, and consequent decrease in SL. After that, the increase in force production might be more dependent on combination of a slightly additional increase of SF and a vaguely maintenance of SL, similar to the reported relation of these parameters with swimming velocity (Barbosa et al., 2010).

The inverse relationship of force and IVV highlighted the importance of propulsive continuity to achieve higher values of force production (Figueiredo et al., 2013b), and their non-linear relationship could be explained by the fact that the neuromuscular activation of several muscles in a multi-segment and multi-joint movement follows the curvilinear force - velocity relationship pattern for a single joint system (Minetti, 2000). Such increase of propulsive continuity was concomitant with the rise of IdC values, presenting a quadratic relationship with force (Seifert et al., 2009), corroborating that to produce higher force values swimmers modify their arm stroke. This changes in arm coordination reflect changes on reduction of relative duration of the non-propulsive phases that, consequently, lead to changes on SR and SL (Chollet et al., 2000; Figueiredo et al., 2013a; Seifert et al., 2007). This coordination, and consequent stroking parameters adaptations, might be interpreted has a response of the swimmer to produce force, demonstrating that its production is directly dependent on motor control and optimal coordination pattern, as a response to the imposed constraints (e.g. hydrodinamic drag) (Seifert et al., 2009).

The IdC changes enabled continuity between the propulsive phases, but this did not necessarily mean higher propulsion generation values since swimmers could slipped through the water. This fact could be explained by the observed inverse relationship, and negative quadratic dependence of force on η_F. A greater propelling efficiency is traditionally associated with a better capacity to produce force (Barbosa et al., 2010; Toussaint et al., 2006), but, since a high SF is required to generate force and η_F was inversely related to SF, consequently a reduction of the propulsion effectiveness has occurred.

Conclusions

Optimization of force production required increases in SF and, consequently, in swimming velocity. Optimal coordination adaptations, enabling continuity of propulsive phases and IVV decreases were essential to produce higher values of force. However, these adaptations did not necessarily guarantee propulsion efficiency as observed by SL and η_F decrease. Hence, the manipulation of the biomechanical variables might be one of the factors through which swimming force could be altered, emphasising the need of its evaluation, identification and intervention as a common practice both in swimming training and competition.

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