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ARTICLE

The effects of intensity on $\dot{V}O_2$ kinetics during incremental free swimming

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Abstract: Swimming and training are carried out with wide variability in distances and intensities. However, oxygen uptake kinetics for the intensities seen in swimming has not been reported. The purpose of this study was to assess and compare the oxygen uptake kinetics throughout low-moderate to severe intensities during incremental swimming exercise. We hypothesized that the oxygen uptake kinetic parameters would be affected by swimming intensity. Twenty male trained swimmers completed an incremental protocol of seven 200-m crawl swims to exhaustion (0.05 m·s^{-1} increments and 30-s intervals). Oxygen uptake was continuously measured by a portable gas analyzer connected to a respiratory snorkel and valve system. Oxygen uptake kinetics was assessed using a double exponential regression model that yielded both fast and slow components of the response of oxygen uptake to exercise. From low-moderate to severe swimming intensities changes occurred for the first and second oxygen uptake amplitudes ($P \le 0.04$), time constants ($P = 0.01$), and time delays ($P \le 0.02$). At the heavy and severe intensities, a notable oxygen uptake slow component (>255 mL·min^{-1}) occurred in all swimmers. Oxygen uptake kinetics whilst swimming at different intensities offers relevant information regarding cardiorespiratory and metabolic stress that might be useful for appropriate performance diagnosis and training prescription.

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

Résumé : La natation et l'entrainement couvrent une large gamme de distances et d'intensités. Toutefois, la cinétique de consommation d'oxygène pour ces intensités observées en natation n'a pas été reportée. Le but de cette étude était ainsi d'évaluer et comparer la cinétique de consommation d'oxygène lors d'intensités de nage de faibles à modérées jusqu'a intenses. Nous faisions l'hypothèse que les paramètres associés seraient affectés par l'intensité d'exercice. Vingt nageurs entraînés ont exécuté un protocole incrémental de sept de 200 m jusqu'à épuisement (incrément de 0.05 m·s^{-1} et intervalle de 30 s), la consommation d'oxygène étant continuellement mesurée par un analyseur de gaz portable relié à un tuba et un système de valves. La cinétique de consommation d'oxygène était évaluée à l'aide d'un modèle de régression à lissage exponentiel double et les paramètres classiques décrivant les composantes lente et rapide. Des changements apparaissent entre les intensités faibles à intenses au niveau des premières et secondes amplitudes de consommation d'oxygène ($P \le 0.04$), constantes de temps ($P = 0.01$) et délais ($P \le 0.02$). Dans les domaines d'intensités difficiles et intenses, tous les nageurs montrèrent une remarque composante lente de la cinétique de consommation d'oxygène (>255 mL·min^{-1}). La cinétique de consommation d'oxygène en nageant à différentes intensités offre des informations pertinentes quant à l'stress cardiorespiratoire et métabolique qui peuvent être utiles à la planification de l'entrainement (en particulier dans la construction de séries plus appropriées), et par suite à l'amélioration de la performance.

Mots-clés : échanges gazeux, cinétique de consommation d'oxygène, exercice, intensités, crawl, modélisation.

Introduction

Oxygen uptake ($\dot{V}O_2$) kinetics analysis has been proposed as a useful tool for swim training and diagnosis (Fernandes and Vilas-Boas 2012; Reis et al. 2012*b*), particularly to improve understanding of tolerance to exercise and the effect that traditional parameters of physiological function (i.e., anaerobic and ventilatory thresholds, maximal oxygen uptake ($\dot{V}O_{2max}$)), and efficiency/economy indicators (Bentley et al. 2007; Hill 2014) have on the $\dot{V}O_2$ response during swimming (Reis et al. 2012*a*; Rodríguez et al. 2003; Sousa et al. 2011).

Traditionally, the analysis of $\dot{V}O_2$ kinetics parameters (i.e., amplitude/s, time constant/s and time delay/s) are used to characterize the $\dot{V}O_2$ dynamics in the low-moderate–, heavy-, severe-, and extreme-exercise intensities (Poole and Jones 2012). The low-moderate–exercise intensity includes all power outputs below (and at) the lactate threshold (LT) boundary, with $\dot{V}O_2$ obtaining a steady state (Robergs 2014) and no change (or only a transient increase) in blood lactate (La) concentrations (Burnley and Jones 2007; Carter et al. 2002). The heavy intensity displays power outputs above the LT, starting with a notable slow component ($\dot{V}O_{2s}$), leading to a higher $\dot{V}O_2$ amplitude (Pringle et al. 2003) and eliciting a significant La accumulation as a function of time (Burnley and Jones 2007). For the severe intensity, the exercise is significantly higher than LT and neither $\dot{V}O_2$ nor La values can be stabilized (Gaesser

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and Poole 1996), showing a pronounced $\dot{V}O_{2s}$ and a greater La accumulation time compared with the previous intensity (Burnley and Jones 2007; Pringle et al. 2003).

Over the last 90 years, $\dot{V}O_2$ 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 and 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 $\dot{V}O_2$ kinetics during the 100- and 400-m front crawl within the extreme intensity response in swimming pool conditions — some recent studies also considered the $\dot{V}O_2$ — focusing on the heavy or severe intensities (e.g., Fernandes et al. 2008; Pessoa Filho et al. 2012; Sousa et al. 2014*b*). Despite this, and knowing that the swimming training process encompasses a wide range of exercise intensities, it seems relevant to evaluate and compare the $\dot{V}O_2$ kinetics during different intensities, particularly including those above the LT but also within the low-moderate–exercise intensity.

The comparison of $\dot{V}O_2$ kinetics across different exercise intensities is not novel in running and cycling (Carter et al. 2000; Koppo et al. 2004; Pringle et al. 2003), and helped scientists to identify how $\dot{V}O_2$-related parameters relate 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 $\dot{V}O_2$ values) during incremental exercise, indicating an evident effect of endurance development on initial $\dot{V}O_2$ adjustments. Thus, findings about the parameters of dynamic $\dot{V}O_2$ 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 correct exercise-intensity prescription.

As no research comparing the $\dot{V}O_2$ kinetics with a wide range of swimming intensities has been done, we used a discontinuous incremental protocol to analyze and compare the $\dot{V}O_2$ 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 in $\dot{V}O_2$ kinetics (nor the appearance of a slow component) would be observed in different velocity bouts within the low-moderate intensity, whereas the time-constant and time-delay values would show noticeable changes within the heavy and severe intensities. Moreover, it was expected that there would be 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, which would be significantly above LT.

Materials 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, 178.2 ± 6.0 cm; fat mass, 10.6% ± 2.1% (InBody230 Co. Ltd, USA); 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 Ethics Committee of Faculty of Sport from the University of Porto approved the research in accordance with the guidelines set forth by the World Medical Association Declaration of Helsinki (2013). All participants (or parent/guardian when subjects were under 18 years old) provided 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, alcohol, nicotine, and other drugs in the 3 h before testing. The experiments took place between 0800 to 1200 hours in a 25-m indoor swimming pool (1.90 m deep) with constant environmental conditions (temperature – water: 27.3 ± 0.1 °C, air: 28.5 ± 0.2 °C; 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 $\dot{V}O_{2max}$ assessment, consisting of seven 200-m swims with 0.05 $m \cdot s^{-1}$ 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 predefined speed of the last step was established according to each swimmer's personal best time at 400-m front crawl at the time of the experiments. Then, 0.05 $m \cdot s^{-1}$ 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 predefined 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, Japan).

Data collection

During the incremental protocol, respiratory gas exchange was assessed using a portable telemetric gas analyzer (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) (Baldari et al. 2013). The gas analyzers were calibrated before each test with gases of known concentration (16% O_2, 5% CO_2) 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 La analysis (Lactate Pro; Arkay Inc., Kyoto, Japan).

Data processing and modeling

Prior to analysis, the collected breath-by-breath $\dot{V}O_2$ data were edited to exclude occasional errant breaths caused by swallowing, coughing, signal interruptions, and so forth, and to improve parameter estimation (Koga et al. 2005). First, values deviating more than 4 SDs 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. $\dot{V}O_2$ data were analyzed for each of the 7 steps of the incremental protocol and were categorized as low-moderate–, heavy-, and severe-exercise intensities (Burnley and Jones 2007; Poole and Jones 2012) according to the intensities corresponding to LT and $\dot{V}O_{2max}$. First, a La-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 $\dot{V}O_{2max}$, namely, the occurrence of a plateau in $\dot{V}O_2$ ($\leq$2.1 $mL \cdot kg^{-1} \cdot min^{-1}$) despite an increase in swimming speed, high levels of maximal La (La_{max}) ($\geq$8 $mmol \cdot L^{-1}$), elevated respiratory exchange ratio ($\geq$1.0), and elevated HR (>90% (220 – age)) (Poole et al. 2008). Then, taking

LT and $\dot{V}O_{2max}$ as metabolic intensity indicators, the 1st to 4th steps were categorized as low-moderate–intensity, as they were under (1st to 3rd) and at (4th step) the LT boundary (i.e., ~35 mL·kg^{-1}·min^{-1}). The 5th and 6th step were considered to be heavy intensity, as they corresponded to an intensity above the LT and below the minimum swimming velocity corresponding to the $\dot{V}O_{2max}$ (Fernandes and Vilas-Boas 2012) (i.e., between 45 and 55 mL·kg^{-1}·min^{-1}), and the 7th step was considered as severe exercise, as it coincided with the step in which $\dot{V}O_{2max}$ was attained (i.e., ~60 mL·kg^{-1}·min^{-1}).

To analyze pulmonary $\dot{V}O_2$ kinetics, weight-related (relative) $\dot{V}O_2$ data (mL·kg^{-1}·min^{-1}) were first modeled using a mono-exponential function:

$$(1) \qquad \dot{V}O_2(t) = \dot{V}O_{2b} + A_1 \cdot [1 - e^{-(t-TD_1)/\tau_1}]$$

where $\dot{V}O_2(t)$ represents the relative $\dot{V}O_2$ at a given time (t); $\dot{V}O_{2b}$ is the baseline, pre-exercise $\dot{V}O_2$ (i.e., averaged for the 20 s before the start of the 200 m step); and A_1, TD_1, and τ_1 are the amplitude, time delay, and time constant, respectively, of the on-transient $\dot{V}O_2$.

In addition, a bi-exponential function was also explored to model the primary (phase II) and slow (phase III) components separately (Barstow and Molé 1987; Rossiter 2011):

$$(2) \qquad \dot{V}O_2(t) = \dot{V}O_{2b} + A_p \cdot [1 - e^{-(t-TD_p)/\tau_p}] + A_s \cdot [1 - e^{-(t-TD_s)/\tau_s}]$$

where $\dot{V}O_2(t)$ and $\dot{V}O_{2b}$ are as in eq. 1; A_p, TD_p, and τ_p are the amplitude, time delay, and time constant, respectively, of the primary component; and A_s, TD_s, and τ_s are the corresponding parameters of the slow component.

The $\dot{V}O_2$ 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 (Fig. 1).

Statistical analysis

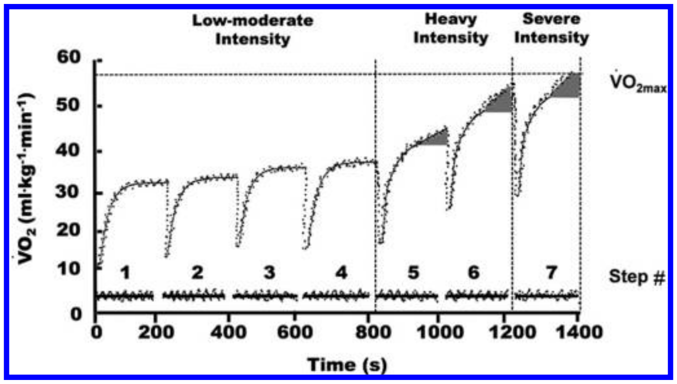
Data are reported as mean values ± SD. The normality of distribution was checked with the Shapiro-Wilk's test. Before statistical analysis of the $\dot{V}O_2$ kinetics parameters, the 2 nonlinear regression fits (i.e., mono- and bi-exponential) were compared for each step of the incremental swimming protocol using an *F*-test approximation. To compare the 3 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 $\dot{V}O_2$ 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 2 nonlinear functions for low-moderate–swimming intensity (P = 0.87), but differences were found for the heavy and severe intensities (P = 0.03); this led us to analyze the $\dot{V}O_2$ kinetics using the double bi-exponential function for all 7-step exercise loads, as displayed in Fig. 1 for a representative subject.

Table 1 shows the $\dot{V}O_2$ parameters estimated using the bi-exponential regression model, as well as HR and La, for each step of the incremental swimming protocol.

Fig. 1. Oxygen uptake ($\dot{V}O_2$) kinetics of a representative subject along the 7-step incremental swimming protocol. Exercise intensities, maximal oxygen uptake ($\dot{V}O_{2max}$) (dashed line), and $\dot{V}O_2$ slow component (grey zone) are identified. The residuals plots of the measured (already smoothed) and estimated $\dot{V}O_2$ values for each step of the incremental exercise are presented below each step.



No significant differences were found among the estimated values for $\dot{V}O_2$ amplitude, TD, and τ in the first 4 exercise loads corresponding to the low-moderate intensity ($P \geq 0.33$). Conversely, all $\dot{V}O_2$ kinetics parameters in the later steps (5th, 6th, and 7th), corresponding to the heavy- and severe-swimming intensities, differed for $\dot{V}O_{2b}$ ($F_{[5,15]}$ = 2.65, P = 0.02) and the rest of parameters of the primary and slow components: A_p ($F_{[3,17]}$ = 6.23, P = 0.01), A_s ($F_{[5,15]}$ = 6.61, P = 0.02), TD_p ($F_{[3,17]}$ = 3.54, P = 0.04), TD_s ($F_{[5,15]}$ = 5.13, P = 0.02), τ_p ($F_{[5,15]}$ = 5.22, P = 0.01), and τ_s ($F_{[3,17]}$ = 3.25, P = 0.01). Thus, a faster $\dot{V}O_2$ kinetics pattern became evident at the 5th and later steps with the appearance of an increased $\dot{V}O_{2s}$ superimposed on the faster primary response $\dot{V}O_{2p}$ ($\Delta\dot{V}O_2$ > 250 mL·min^{-1}) (Table 1, Fig. 1). As expected, HR and La values progressively increased and were significantly higher while swimming at heavy ($F_{[2,18]}$ = 4.21, P = 0.02) and severe intensities ($F_{[2,18]}$ = 6.69, P = 0.03) compared with the low-moderate–intensity loads.

Discussion

This study investigated the on-transient $\dot{V}O_2$ kinetics during an incremental swimming test from rest to maximal exercise eliciting $\dot{V}O_{2max}$ across the low-moderate to severe intensities in competitive swimmers. The main findings were (*i*) the $\dot{V}O_2$ kinetics pattern remained stable within the range of intensities corresponding to the low-moderate intensity (up to the LT boundary), reaching a steady state; and (*ii*) conversely, across the heavy- and severe-exercise intensities (above LT) faster ($\dot{V}O_2$ kinetics shorter time-constant and time-delay values) and greater $\dot{V}O_2$ gains in the primary component were noted, with the appearance of a noticeable slow component at ~130 s ($\Delta\dot{V}O_2$ > 250 mL·min^{-1}). As a central interpretation of these findings, one could argue that the changes observed in the $\dot{V}O_2$ 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. 2015; Sousa et al. 2014*a*).

The vast majority of studies in the field have been performed using cycle ergometry and provided important insights concerning the time-course of the $\dot{V}O_2$ responses across a wide range of intensities (e.g., Poole and Jones (2012) for a review). Nonetheless, differences in the response across different exercise modalities (Jones and Burnley 2005) and exercise intensity (Carter et al. 2002; Özyener et al. 2001; Rossiter 2011) do exist. Our results, on the 1 hand, show that the basic features of the $\dot{V}O_2$ kinetics response to low-moderate, heavy, and severe intensities in swimming are similar to other modes of exercise, confirming the concept that $\dot{V}O_2$ kinetics is modulated by the same fundamental mechanisms. On the other hand, though, differences arise as this is the first study to provide detailed analysis of the $\dot{V}O_2$ dynamics using a single incremental exercise protocol across a very wide range of intensities 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 2011). Using this

Table 1. Oxygen uptake estimated parameters extracted from the bi-exponential regression model in each step of the incremental swimming protocol.

	Low-moderate domain				Heavy domain		Severe domain
Step no.:	1	2	3	4	5	6	7
$\dot{V}O_{2b}$ (mL·kg⁻¹·min⁻¹)	$8\pm1^{5-7}$	$9\pm1^{5-7}$	$9\pm1^{5-7}$	$9\pm1^{5-7}$	$13\pm2^{6,7}$	14 ± 2^{7}	16 ± 2
A_p (mL·kg⁻¹·min⁻¹)	$20\pm7^{5-7}$	$21\pm8^{5-7}$	$23\pm5^{5-7}$	$23\pm6^{5-7}$	$27\pm8^{6,7}$	36 ± 8^{7}	37 ± 9
A_s (mL·kg⁻¹·min⁻¹)	$1\pm1^{5-7}$	$1\pm1^{5-7}$	$1\pm1^{5-7}$	$1\pm1^{5-7}$	$4\pm2^{6,7}$	6 ± 2^{7}	9 ± 3
A_s (mL·min⁻¹)	$80\pm2^{5-7}$	$81\pm3^{5-7}$	$80\pm2^{5-7}$	$82\pm2^{5-7}$	$256\pm3^{6,7}$	451 ± 4^{7}	631 ± 4
TD_p (s)	$13\pm10^{5-7}$	$12\pm11^{5-7}$	$11\pm8^{5-7}$	$12\pm8^{5-7}$	10 ± 4^{7}	8 ± 4	8 ± 3
TD_s (s)	$150\pm48^{5-7}$	$151\pm43^{5-7}$	$150\pm27^{5-7}$	$149\pm39^{5-7}$	127 ± 36^{7}	126 ± 25	125 ± 28
τ_p (s)	$15\pm7^{5-7}$	$15\pm1^{5-7}$	$16\pm6^{5-7}$	$15\pm2^{5-7}$	10 ± 3^{7}	9 ± 3^{7}	8 ± 4
τ_s (s)	$181\pm28^{5-7}$	$182\pm76^{5-7}$	$181\pm33^{5-7}$	$179\pm53^{5-7}$	$169\pm62^{6,7}$	171 ± 61^{7}	158 ± 53
$\dot{V}O_{2peak}$ (mL·kg⁻¹·min⁻¹)	$34\pm1^{5-7}$	$36\pm2^{5-7}$	$37\pm2^{5-7}$	$38\pm3^{5-7}$	$45\pm2^{6,7}$	55 ± 2^{7}	58 ± 2
Heart rate (beats·min⁻¹)	$131\pm3^{2-7}$	$147\pm3^{3-7}$	$154\pm3^{4-7}$	$161\pm5^{5-7}$	$165\pm4^{6,7}$	172 ± 2^{7}	188 ± 1
La_{max} (mmol·min⁻¹)	$1.3\pm0.3^{3-7}$	$1.4\pm0.4^{3-7}$	$1.8\pm0.9^{4-7}$	$2.6\pm0.6^{5-7}$	$4.5\pm1.0^{6,7}$	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

Note: Data are means ± SD. Superscripts represent values significantly different from noted steps (e.g., $^{5-7}$, different from steps no. 5 to 7; ^{5,6,7}, different from nos. 5, 6, and 7) (ANOVA, Sidak's post hoc test, $P < 0.05$). Heart rate and blood lactate concentrations are also shown. A_p and A_s, amplitude of the primary and slow components, respectively; HR, heart rate; La_{max}, blood lactate concentration and time length of each of the steps; τ_p and τ_s, time constants amplitude of the primary and slow component, respectively; TD_p and TD_s, time delay of the primary and slow components, respectively; $\dot{V}O_{2b}$, baseline oxygen uptake; $\dot{V}O_{2peak}$, peak oxygen uptake.

approach, researchers and coaches are able to assess several key physiological features useful for diagnosis and training in swimming: aerobic fitness (Reis et al. 2012*a*), exercise tolerance (Burnley and Jones 2007; Jones and Burnley 2009), maximal aerobic power (Fernandes et al. 2003; Rodríguez et al. 2003), velocity at $\dot{V}O_{2max}$ (Sousa et al. 2014*b*), individual LT and ventilatory 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. 2012*b*; 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. 2015; 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 appropriate methods to quantify $\dot{V}O_2$ 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. 2012*a*) that discriminates the different $\dot{V}O_2$ components (Robergs 2014; Sousa et al. 2014*b*), although whether 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 and Rossiter 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 the $\dot{V}O_{2max}$) (Demarie et al. 2001; Fernandes et al. 2008; Sousa et al. 2014*b*).

Focusing on the present results, similar $\dot{V}O_2$ kinetics parameters were observed along the 4 protocol steps conducted within the low-moderate intensity, which is in line with studies conducted in other cyclic sports (Robergs 2014). The $\dot{V}O_2$ baseline values (~9 mL·kg⁻¹·min⁻¹ on average) showed low variability similar to previous results in well-trained swimmers (Reis et al. 2013) and in runners and cyclists (Caputo et al. 2003; Carter et al. 2000). The $\dot{V}O_2$ amplitude during the first 4 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 (McLean et al. 2010) despite an elevated respiratory work (Ogita and 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 subjects can attain a $\dot{V}O_2$ steady-state within ~2 min of low-moderate–intensity exercise (Fig. 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; Reis et al. 2013; Roels et al. 2005). These suggest that at intensities at or below the La threshold, ATP resynthesis can be achieved via oxidative phosphorylation, a $\dot{V}O_2$ steady-state is attained and a low production and fast removal of La occurs, with a consequently low-La accumulation (Burnley and Jones 2007; Mader et al. 1983). Finally, the observed HR values were also in accordance with reference values (≤160 beats·min⁻¹) proposed for exercise intensity conducted at low-moderate intensity (Poole and Jones 2005).

Comparison of $\dot{V}O_2$ 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 $\dot{V}O_2$ baseline values were higher than those presented for running and cycling square-wave exercises (Carter et al. 2002; Cleuziou et al. 2004; Pringle et al. 2003), as frequently observed in swimming exercise (e.g., Fernandes et al. 2008; Reis et al. 2012*a*; 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 K4 b² unit) prior to entering the swimming pool and begining 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 baseline values of $\dot{V}O_2$, 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. 2012*a*). According to Carter et al. (2000) and Pringle et al. (2003), this increased amplitude can be due to the higher $\dot{V}O_2$ demand since intensity and respiratory effort increase. This fact is observed in Fig. 1 (heavy and severe intensity), where higher $\dot{V}O_2$ 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.

2012*a*). In fact, the A_s has been commonly reported for heavy (Reis et al. 2012*a*), but mainly for severe swimming intensities (Billat 2000; Fernandes et al. 2008; Sousa et al. 2014*b*). However, when assessing A_s for a single exercise bout, Reis et al. (2012*a*) and Fernandes et al. (2008) reported values between 350 and 356 mL·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 on moderate and heavy (Carter et al. 2000) and moderate and severe intensities (Cleuziou et al. 2004), evidencing that the 30-s rest intervals in-between steps have some influence in the $\dot{V}O_2$ 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. 2014*b*). This can be due to the fact that swimming is performed in a horizontal position, influencing the cardiorespiratory and metabolic demands compared with other land-based sports such as cycling and running (Aspenes and Karlsen 2012). In fact, it has been suggested that exercising while in a horizontal position induces a lower sympathetic stimulation, $\dot{V}O_2$ 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; Koppo 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 fiber types responsible for force production (Koppo et al. 2004). Despite the appearance of an evident slow component within the heavy and severe exercises, all these studies suggest that at higher intensities swimmers would benefit more from a lower duration of each set of exercise during intermittent aerobic training work. This would be due to the faster occurrence of the $\dot{V}O_2$ 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 $\dot{V}O_2$ 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 with 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 to take into consideration if they used an individual square-wave intensity or progressive-intensities protocols. Finally, it is also important to mention that step tests with set velocity increments do not increase by a set power increment due to nonlinear velocity-power relationships. Future experiments should be carried out trying to better characterize the underlying mechanism regarding the $\dot{V}O_2$ dynamic behavior in different groups of swimmers and exercise conditions, as obvious differences on $\dot{V}O_2$ kinetics parameters between groups were found when using different exercise types. Also exploring the extreme exercise intensity, i.e., above $\dot{V}O_{2max}$ intensity, would be of particular interest.

Conclusions

The present findings showed that the fast and slow $\dot{V}O_2$ components changed from low to severe swimming intensities (i.e., progressively greater $\dot{V}O_2$ amplitudes and faster time constants) and that the well-known 7 × 200-m incremental protocol is suitable to assess these differences. Within the bouts performed at low-moderate intensity, swimmers showed great stability in all $\dot{V}O_2$ kinetics parameters, whereas at the heavy and severe intensities, faster $\dot{V}O_2$ kinetics and a pronounced $\dot{V}O_2$ slow component occurred. Since swimmers typically train in a wide range of intensities, understanding the subtle $\dot{V}O_2$ kinetics modifications that take place across different training zones might have important implications for optimizing training intensities prescription.

Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this paper.

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