

$\dot{V}O_2$ kinetics and metabolic contributions during full and upper body extreme swimming intensity

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Abstract

Purpose Our purpose was to characterize the oxygen uptake ($\dot{V}O_2$) kinetics, assess the energy systems contributions and determine the energy cost when swimming front crawl at extreme intensity. Complementarily, we compared swimming full body with upper body only.

Methods Seventeen swimmers performed a 100 m maximal front crawl in two conditions: once swimming with full body and other using only the upper propulsive segments. The $\dot{V}O_2$ was continuously measured using a telemetric portable gas analyser (connected to a respiratory snorkel),

and the capillary blood samples for lactate concentration analysis were collected.

Results A sudden increase in $\dot{V}O_2$ in the beginning of exercise, which continuously rose until the end of the bout (time: 63.82 ± 3.38 s; $\dot{V}O_{2peak}$: 56.07 ± 5.19 ml min⁻¹ kg⁻¹; $\dot{V}O_2$ amplitude: 41.88 ± 4.74 ml min⁻¹ kg⁻¹; time constant: 12.73 ± 3.09 s), was observed. Aerobic, anaerobic lactic and alactic pathways were estimated and accounted for 43.4, 33.1 and 23.5 % of energy contribution and 1.16 ± 0.10 kJ m⁻¹ was the energy cost. Complementarily, the absence of lower limbs lead to a longer time to cover 100 m (71.96 ± 5.13 s), slower $\dot{V}O_2$ kinetics, lower aerobic and anaerobic (lactic and alactic) energy production and lower energy cost.

Conclusion Despite the short duration of the event, the aerobic energy contribution covers about 50 % of total metabolic energy liberation, highlighting that both aerobic and anaerobic energy processes should be developed to improve the 100 m swimming performance. Lower limbs action provided an important contribution in the energy availability in working muscles being advised its full use in this short duration and very high-intensity event.

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Energy contribution · Energy cost · Front crawl

Abbreviations

A	Oxygen uptake amplitude
AnAl	Anaerobic alactic
AnL	Anaerobic lactic
β	Energy equivalent for blood lactate accumulation
M	Mass of the subject
min	Minutes
PCr	Phosphocreatine concentration

s	Seconds
S_{full}	Swimming full body
S_{upper}	Swimming upper body
t	Time
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2b}$	Basal oxygen uptake
$\dot{V}O_{2\text{max}}$	Maximal oxygen uptake
$\dot{V}O_{\text{peak}}$	Peak oxygen uptake
τ	Time constant
$[\text{La}^-]$	Lactate concentration
$[\text{La}^-]_{\text{max}}$	Maximal lactate concentration

Introduction

Competitive pool swimming events, vary from short (50 m, ~20 s) to long distances (1500 m, ~15 min), are performed at different intensities and place specific energetic demands on the metabolic system (Capelli et al. 1998; Figueiredo et al. 2011; Olbrecht 2000; Reis et al. 2010; Zamparo et al. 2000). In fact, performing a ~20 s effort involves the use of completely different metabolic pathways compared to those involved with longer swimming event lasting ~15 min (Olbrecht 2000). Hence, the understanding of the metabolic profile of each swimming event of a swimmer is important, for designing appropriate training programs, to improve performance.

Studies that aimed at the determination of swimming energetics focused mainly on the assessment of oxygen consumption ($\dot{V}O_2$), but despite its response as a function of exercise intensity is well documented, researchers generally analysed it from low to severe swimming domains (de Jesus et al. 2014; Pessoa Filho et al. 2012; Reis et al. 2012a, 2013; Sousa et al. 2014). As the majority of the races are typically swum at faster paces (the duration of the 50, 100 and 200 m front crawl is within 2 min of exercise), measuring $\dot{V}O_2$ at lower intensities has limited application for a better understanding of the oxygen delivery to the working muscles as a performance limiting factor in swimming. In fact, research regarding $\dot{V}O_2$ kinetics assessment at extreme intensities compatible with race-like swimming conditions is scarce, existing only two studies that aimed to characterize the $\dot{V}O_2$ kinetics at 100 m (pilot study; Rodriguez et al. 2003) and 200 m (Sousa et al. 2011) front crawl.

Moreover, recently it has been suggested that, even for short duration swimming events, there is a relevant aerobic energy contribution that should be taken into consideration in the training process (Figueiredo et al. 2011; Peyrebrune et al. 2014). However, the available information regarding the relative contribution of each energy system to the overall energy supply of short duration but very intense swimming events is scarce. Assessing the total energy expenditure and the energy cost of extreme swimming intensity events by considering aerobic, anaerobic lactic and alactic

energy sources is an almost unexplored territory, with the exception of two studies conducted over 91.4 m (Capelli et al. 1998) and 200 m (Figueiredo et al. 2011) front crawl.

In addition, the $\dot{V}O_2$ kinetics, the energy expenditure and, consequently, the energy cost of swimming, depends on the amount of muscle mass involved in the exercise, particularly regarding lower limbs action contribution to the overall swimming propulsion. However, its importance in short and very intense swimming has been neglected since the lower limbs action is traditionally considered not very relevant due to the additional energy cost and the lack of evident benefits for propulsion (Toussaint et al. 1990a). In fact, no study has considered the effect of lower limbs' action on $\dot{V}O_2$ kinetics, although few studies analyzed its influence on the aerobic and anaerobic contributions (but by performing in swimming flume conditions that is different from swimming freely in a pool; Ogita et al. 1996, 2003). As it was recently suggested that a higher lower limbs action could present a positive effect on the overall propulsion, and that it could play an important role in coordination and wave drag and trunk inclination reduction during sprint front crawl swimming (Gourgoulis et al. 2014; Toussaint 2011), the metabolic consequences of using an active action of the lower limbs on the overall swimmer's energetic profile should be analysed.

The purpose of this study was to characterize the $\dot{V}O_2$ kinetics, estimate the different energy systems contribution and calculate from that the energy cost of swimming at the extreme-intensity domain. Complementarily, the referred physiological parameters were used to compare swimming full body with performing only with upper body, as it is suspected that the amount of active muscle mass will influence the metabolic demand and, therefore, superior energy cost of exercise.

Methods

Seventeen well-trained male swimmers (mean \pm SD 17.47 \pm 1.84 years of age, 1.80 \pm 0.06 m of height, 70.76 \pm 6.56 kg of body mass, 11.31 \pm 3.46 years of training background, ≥ 7 units per week of training frequency) were tested. Their best performance in 100-m freestyle long course swimming was 56.26 \pm 2.42 s, corresponding to 117.94 \pm 11.71 % of 100-m freestyle world male record. Participants volunteered to participate and provided informed written consent (or parent/guardian when subjects were under 18 years) before data collection. Swimmers avoided strenuous exercise and abstained from smoking and consuming alcohol or caffeine 48 h prior to exercise testing, and were previously familiarized with the procedures and experimental equipment (previously approved by the local ethics committee and performed 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 27.5 °C and 60 % of air humidity. Each swimmer accomplished two testing sessions, separated by at least 24 h rest. Following a randomized order, in one session the subjects performed 100 m front crawl at maximum intensity swimming full body (S_{full}) and, in the other session, using only the upper body (S_{upper} , with the lower limbs supported by a standard pull-buoy). The buoyancy of the pull-buoy was 15.0 N when fully immersed and, since relative buoyancy for the lower limbs differed in-between subjects, it was checked if the swimmers' lower limbs were kept in a horizontal streamlined position during the entire bout. The two experimental conditions were preceded by an individual warm-up consisting on 15 min of low to moderate intensity. Ten minutes of passive rest were taken between warm-up and exercise bout to ensure that previous workout did not influence $\dot{V}O_2$ kinetics and exercise tolerance of the subsequent bout (Bailey et al. 2009). In-water starts and open turns (without gliding) were used in both S_{full} and S_{upper} .

$\dot{V}O_2$ was directly and continuously measured using a telemetric portable gas analyzer (K4b², Cosmed, Rome, Italy) connected to a specific respiratory snorkel and valve system (Aquatrainer, Cosmed, Rome, Italy), which is a breath-by-breath low hydrodynamic resistance device (Baldari et al. 2013; Ribeiro et al. 2011) that allows swimming without restrictions. Previously to the experiment, the device reference air calibration was performed using a gas sample (16 % oxygen and 5 % carbon dioxide concentrations) and the flow meter was calibrated with a 3,000 ml syringe.

Capillary blood samples for lactate concentration [La^-] analysis were collected from the earlobe at rest, at the end of exercise and in the recovery period (at 1, 3 and 5 min), and were analyzed using a portable lactate analyzer (Lactate Pro, Arkray, Inc., Kyoto, Japan). Prior to each test, the device was calibrated according to manufacturer's specifications.

Data analysis

First, the $\dot{V}O_2$ breath values were omitted from the analysis by including only those in-between mean \pm 4 SD. Afterwards, individual $\dot{V}O_2$ responses were smoothed using a 3-breath moving average and time-average to produce a standard weighted response at 5 s intervals (Sousa et al. 2011). For $\dot{V}O_2$ kinetics analysis, the data after the onset of exercise were fitted using the iterative Levenberg–Marquardt algorithm to a mono-exponential model, where a nonlinear least squares method was implemented in Matlab environment for the adjustment of the function to $\dot{V}O_2$ data:

$$\dot{V}O_2 = \dot{V}O_{2b} + A \times (1 - e^{(t/\tau)})$$

where t (s) is the time, $\dot{V}O_{2b}$ ($\text{ml kg}^{-1} \text{min}^{-1}$) the basal oxygen uptake at the start of the exercise, A ($\text{ml kg}^{-1} \text{min}^{-1}$) is the $\dot{V}O_2$ amplitude and τ (s) stands for the time constant. The peak oxygen uptake ($\dot{V}O_{2\text{peak}}$) was obtained from the highest $\dot{V}O_2$ value recorded during the exercise.

Regarding the different energy systems contribution, the aerobic participation was calculated from the time integral of the net $\dot{V}O_2$ versus time relationship (Figueiredo et al. 2011; Sousa et al. 2014). The anaerobic contribution was estimated using a methodology (recognized to be valuable to have an approximation of the anaerobic energy demands during supra-maximal exercise in several forms of locomotion, as reviewed by Zamparo et al. 2011) that considers the sum of the energy derived from lactic acid production with the one derived from phosphocreatine splitting in the contracting muscles. The lactic contribution (AnL) was calculated using the following equation (Figueiredo et al. 2011; Sousa et al. 2014):

$$\text{AnL} : \beta \times [\text{La}]_{\text{net}} \times M$$

where $[\text{La}]_{\text{net}}$ is the difference between the blood lactate accumulation after and before exercise, β the energy equivalent for blood lactate accumulation ($2.7 \text{ ml O}_2 \text{ mM}^{-1} \text{ kg}^{-1}$, di Prampero et al. 1978) and M is the mass of the subject. The anaerobic alactic contribution (AnAl) was obtained considering (Capelli et al. 1998; Figueiredo et al. 2011; Sousa et al. 2013, 2014; Zamparo et al. 2011):

$$\text{AnAl} : \text{PCr} (1 - e^{-t/\tau})$$

where t is the time duration, τ the time constant of phosphocreatine splitting at work onset (23.4 s; Binzoni et al. 1992), M the mass of the subject and PCr is the phosphocreatine concentration at rest assumed to be $18.5 \text{ m-mole kg}^{-1}$ (Capelli et al. 1998; Sousa et al. 2013, 2014; Zamparo et al. 2011). The energy derived from the utilization of the phosphocreatine stores was estimated assuming that, in the transition from rest to exhaustion, its concentration decreases by $18.5 \text{ m-mole kg}^{-1}$ muscle (wet weight) in maximally active muscle mass (assumed to correspond to 30 and 20 % of body mass in S_{full} and S_{upper} conditions, respectively). To express the energy expenditure in kJ in the anaerobic alactic contribution, it was assumed a phosphorus/oxygen ratio of 6.25 and an energy equivalent of $0.468 \text{ kJ m-mole kg}^{-1}$ (Capelli et al. 1998), while for the aerobic and anaerobic lactic energy contributions the energy equivalent was $20.9 \text{ kJ l O}_2^{-1}$ (Figueiredo et al. 2011; Sousa et al. 2014; Zamparo et al. 2011). Based on these overall data, energy expenditure was assessed and energy cost was obtained as the ratio between energy expenditure and distance. The energy cost based on mechanical requirements was also estimated for comparison. Hence, assuming mechanical

efficiency as 10 %, propelling efficiency as 70 % and drag as $30 \times \text{velocity}^2$ the estimated energy per metre $[(1/\text{mechanical efficiency}) \times (1/\text{propelling efficiency}) \times (\text{drag} \times 1 \text{ m})]$ was obtained (Toussaint 2011; Toussaint et al. 1988, 1990b).

Statistical analysis

The normality of the data distribution was checked using the Kolmogorov–Smirnov test and descriptive statistics (mean \pm SD) from all measured variables were calculated. A paired sample *t* test was used to compare differences between S_{full} and S_{upper} conditions (level of significance was set at 5 %).

Results

An individual example of the $\dot{V}O_2$ uptake kinetics during maximal S_{full} and S_{upper} bouts is presented in Fig. 1. At the beginning of the swim, the S_{full} condition revealed an instantaneous and sudden $\dot{V}O_2$ increase, while a more moderate rise was observed in S_{upper} . In both circumstances, $\dot{V}O_2$ continued to augment until the end of the bout (that ended later when swimming using only the upper body).

Mean \pm SD values of time duration, speed, $\dot{V}O_{2\text{peak}}$, A , τ and $[\text{La}^-]$ during the maximal bouts are given in Table 1. When swimming full body, swimmers performed faster (13.70 ± 4.31 %), developed a faster $\dot{V}O_2$ kinetics (as indicated by the lower τ values) and attained higher $\dot{V}O_{2\text{peak}}$, A and $[\text{La}^-]$ values ($p < 0.001$).

To control the effect of different O_2 demands and time duration between S_{full} and S_{upper} conditions, $\dot{V}O_2$ responses were normalized to the difference between $\dot{V}O_{2b}$ and $\dot{V}O_{2\text{peak}}$, and time was expressed as percentage of bout duration, respectively, of each condition tested. The normalized $\dot{V}O_2$ response during maximal S_{full} and S_{upper} is presented in Fig. 2 for a representative subject.

As observed for the absolute values, the relative τ value in S_{full} was lower than S_{upper} condition: 28.88 ± 8.86 vs 36.22 ± 13.54 % ($p = 0.03$), respectively.

During this short duration and very high-intensity swim, the energy resulting from aerobic, anaerobic lactic and alactic pathways when swimming full body were higher than those founded when performing only with the upper body: 49.31 ± 3.91 vs 45.12 ± 9.51 ($p = 0.04$), 39.01 ± 7.90 vs 26.98 ± 8.70 ($p < 0.001$) and 27.19 ± 2.51 vs 18.87 ± 1.72 kJ ($p < 0.001$), respectively.

The estimation for energy liberation for the different metabolic sources to the total energy expenditure during the 100 m front crawl maximal bouts is reported in Fig. 3, being observed that aerobic pathway had the highest

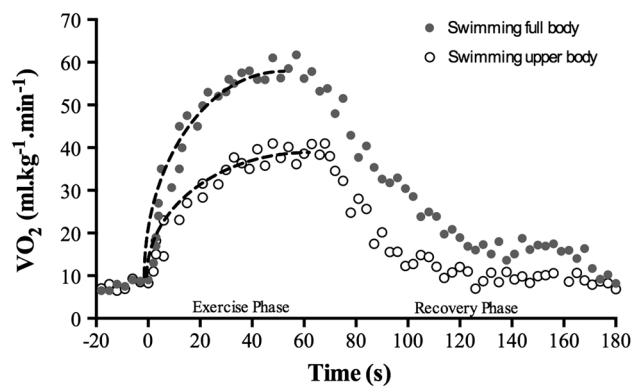


Fig. 1 Typical example of a swimmer's oxygen uptake ($\dot{V}O_2$) kinetics during an extreme-intensity swimming bout (100 m front crawl) using full body and upper body only

percentage contribution (followed by anaerobic lactic and alactic systems) for both S_{full} and S_{upper} conditions. Compared to S_{full} condition, swimming only with the upper body presented higher aerobic ($p = 0.001$) and lower anaerobic lactic ($p = 0.03$) and alactic ($p = 0.001$) percentage contributions.

Moreover, the energy cost was higher in S_{full} (1.16 ± 0.10 kJ m^{-1}) in comparison to S_{upper} (0.91 ± 0.12 kJ m^{-1} , $p < 0.001$). When these values were compared to the energy cost values estimated by mechanical requirements, no differences were observed between them for both S_{full} (1.23 ± 0.13 kJ m^{-1} , $p = 0.12$) and S_{upper} (0.98 ± 0.15 kJ m^{-1} , $p = 0.10$).

Discussion

The purpose of this study was to characterize the $\dot{V}O_2$ kinetics, estimate the energy system contributions and assess the energy cost of locomotion in one of the most attractive swimming events—the 100 m freestyle (usually performed in front crawl)—that well represents performance at the extreme-intensity domain. Complementarily, the influence of the use (or absence) of the lower limbs action was analysed. Our main findings could be summarized as follows: (a) a fast increase of the $\dot{V}O_2$ occurred at the beginning of the swim and continued to rise during the exercise, implying a high $\dot{V}O_2$ demand; (b) an equal contribution of aerobic and anaerobic pathways to total energy liberation was found (if the participations of both lactic and alactic pathways are considered); and (c) the energy cost values were high (>1.0 kJ m^{-1}). Complementarily, the absence of lower limbs action lead to a slower $\dot{V}O_2$ kinetics, induced lower aerobic and anaerobic (lactic and alactic) energy demand and revealed an inferior energy cost.

Table 1 Mean \pm SD of time duration, speed, peak oxygen uptake ($\dot{V}O_{2peak}$), oxygen uptake amplitude (A) and time constant (τ), as well as maximal lactate concentrations ($[La^-]_{max}$), after the maximal 100 m front crawl bouts performing with full body (S_{full}) and upper body only (S_{upper})

	Time (s)	Speed (m s ⁻¹)	$\dot{V}O_{2peak}$ (ml kg ⁻¹ min ⁻¹)	$\dot{V}O_{2peak}$ (l min ⁻¹)	A (ml kg ⁻¹ min ⁻¹)	A (l min ⁻¹)	τ (s)	$[La^-]_{max}$ (mmol l ⁻¹)
S_{full}	63.82 \pm 3.38	1.58 \pm 0.07	56.07 \pm 5.19	3.97 \pm 0.49	41.88 \pm 4.74	2.96 \pm 0.39	12.73 \pm 3.09	11.25 \pm 1.60
S_{upper}	71.96 \pm 5.13 ^a	1.39 \pm 0.09 ^a	45.16 \pm 5.73 ^a	3.21 \pm 0.59 ^a	34.21 \pm 6.99 ^a	2.43 \pm 0.61 ^a	17.36 \pm 5.33 ^a	8.01 \pm 1.79 ^a

^a Different from the S_{full} condition

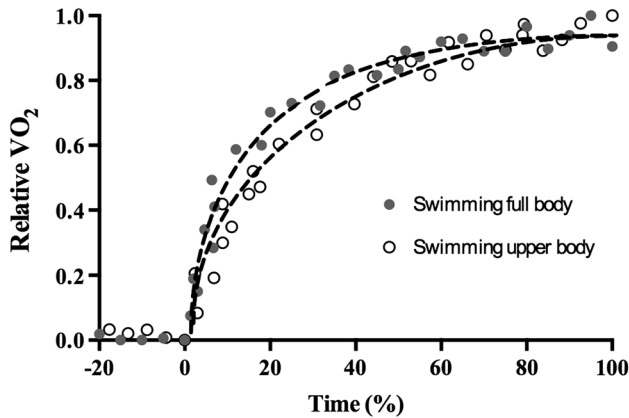
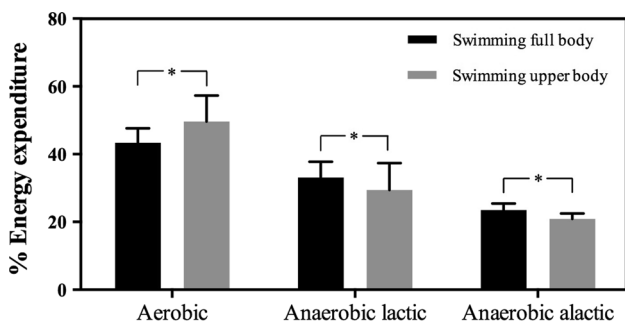


Fig. 2 Typical example of a swimmer’s oxygen uptake ($\dot{V}O_2$) kinetics normalized to $\dot{V}O_{2peak}$ and time percentage during extreme-intensity swimming bout (100 m front crawl) using full body and upper body only



* Different from the swimming full body condition

Fig. 3 Total energy expenditure derived from aerobic, anaerobic lactic and alactic energy sources in the maximal 100 m front crawl conditions

Regarding the $\dot{V}O_2$ kinetics, an instantaneous and sudden increase in $\dot{V}O_2$ from the beginning of the swim was observed that, continued to rise along the exercise. In fact, during extreme exercise intensity $\dot{V}O_2$ is not plateauing and continues to increase until the point of fatigue, precluding the $\dot{V}O_{2max}$ attainment (Burnley and Jones 2007). Moreover, the observed $\dot{V}O_{2peak}$ values were similar to those obtained for the 100 m front crawl (Reis et al. 2010;

Rodriguez et al. 2003), but lower than those presented for the 200 m front crawl (Sousa et al. 2011), evidencing that appropriate oxygen supply and utilization should not be neglected even in short duration swimming efforts (if conducted at maximal intensity). Corroborating these findings, the $\dot{V}O_2$ mean amplitude value was not only comparable to that previously described for extreme intensity effort (Sousa et al. 2011), but also similar to the values observed for severe intensity swimming (Fernandes and Vilas-Boas 2012; Reis et al. 2012b; Sousa et al. 2014), where $\dot{V}O_{2max}$ is commonly attained. Nevertheless, it is important to note that these comparisons did not consider the eventual $\dot{V}O_{2max}$ dissimilarities among subjects of the different reported studies.

In addition, we have found lower τ values than those reported previously for 100 m front crawl (22.7 s; Rodriguez et al. 2003), being important to evidence that a specific distance performed at maximal intensity (i.e. with a “fast start”, as we have conducted) leads to inferior τ values than the same distance performed at an even pace (Jones et al. 2008). This faster $\dot{V}O_2$ kinetics is related with a shorter time lag in the unbalance of $\dot{V}O_2$ demand and supply, implying an augmented oxidative contribution to energy transfer (Burnley and Jones 2007). Complementarily, the reported τ values were lower than those obtained for longer swimming distances (200 m; Sousa et al. 2011 and 400 m front crawl; Rodriguez et al. 2003), since this parameter mathematically describes the $\dot{V}O_2$ kinetics profile reflecting the response of cardiovascular and muscular systems at the selected intensity (Markovitz et al. 2004). Hence, the very high swimming intensity of the 100 m swim (implying the sudden and exponential need of $\dot{V}O_2$) justifies the observed lower τ values.

Regarding the energy requirement, different methodologies have been applied to estimate the energy sources. The aerobic contribution in swimming is traditionally evaluated by (a) directly measuring $\dot{V}O_2$ (Figueiredo et al. 2011; Ogita 2006; Reis et al. 2010; Sousa et al. 2014; Troup 1991), (b) estimating $\dot{V}O_2$ based on $\dot{V}O_{2max}$ (Capelli et al. 1998; Zamparo et al. 2011) and (c) measuring $\dot{V}O_2$ only during the recovery period using the backward extrapolation technique (Zamparo et al. 2000). In the current study, we directly measured $\dot{V}O_2$, which presents the advantage

of having “true” measured values rather than an indirect estimate, despite the minor constraints associated to the use of snorkel device with valve system. The aerobic requirement found in the present study was similar to the values reported for a 100 m (53 %; Troup 1991 and 48 %; Zamparo et al. 2000) and 1 min maximal front crawl swim (50 %; Ogita 2006), but not in agreement with a 100-yard (33 %; Capelli et al. 1998) and 100 m front crawl all-out efforts (69 %; Reis et al. 2010). These discrepancies could be related to the distinct swimmer’s performance level to the different methodologies used to estimate the energy sources, and/or to the different lengths of the bouts. Considering the estimation of the anaerobic requirement, the used approach in the current study is considered valid and not affected by major errors (Capelli et al. 1998; Sousa et al. 2013), despite some questionable assumptions on the calculation of parameters regarding anaerobic contribution (e.g. the energy equivalent of lactate, working muscle mass). Moreover, this methodology takes into consideration anaerobic requirement partitioned by alactic and lactic energy sources, essential for the energy expenditure determination at very high-intensity swimming. Hence, not accounting separately the anaerobic energy sources might result in an underestimation of energy expenditure, with impact on the understanding of performance in short competitive events (Capelli et al. 1998; Figueiredo et al. 2011). On the contrary, the alternative methodology, based on the maximal accumulated oxygen deficit does not enable the alactic energy contribution assessment, and is a time-consuming procedure (submaximal bouts are required) as well as supported by theoretical assumptions (e.g. linearity increase of $\dot{V}O_2$ demand with exercise intensity, constancy of $\dot{V}O_2$ from the onset of exercise), which contribute to some imprecision (Medbo 1996; Reis et al. 2010). Regarding the above-referred studies, the anaerobic requirement was 31 % (Reis et al. 2010), 48 % (Troup 1991), 50 % (Ogita 2006) assessed by means of maximal accumulated oxygen deficit. Using the same methodology of the current study, Zamparo et al. (2000) reported 52 % of anaerobic requirement but only Capelli et al. (1998) computed separately the lactic and alactic contributions that were similar (19.6 %) and higher (47.2 %), respectively, compared to our data. In fact, some underestimation of the anaerobic demand could exist, probably related to task complexity constraints of the current study, particularly the impossibility to perform flip turns and starts that tends to decrease the average speed, thereby increasing the exercise duration. Nevertheless, comparing to a 200 m front crawl effort, both anaerobic lactic and alactic relative energy contribution (13.6 and 20.4 %, respectively; Figueiredo et al. 2011) were lower than the current data, indicating that, despite in the same intensity domain, the anaerobic requirement was less important for the 200 m in comparison to the 100 m.

Studies that examined the energy cost assessment at the extreme intensity and in race-like swimming conditions are very scarce. Comparing to our results (both metabolic and mechanical energy cost estimations), elite male swimmers presented a superior energy cost value (1.73 kJ m^{-1} , over a 91.4 m front crawl distance) at a superior velocity (1.75 m s^{-1} ; Capelli et al. 1998), suggesting that swimming performances in short and very high-intensity events are metabolic-dependent rather than exercise economy dependent. Nevertheless, some caution in data interpretation should be taken, since different methodological procedures might slightly influence the energy cost values. In fact, Zamparo et al. (2000) found higher energy cost values (1.3 kJ.m^{-1}) for young male swimmers during 100 m front crawl maximal swim at 1.50 m s^{-1} . However, taking as reference the energy cost at $\dot{V}O_{2\text{max}}$ intensity ($\sim 400 \text{ m}$ front crawl), our values were higher compared with those of highly trained swimmers (0.61 kJ m^{-1} ; Fernandes et al. 2006), possibly due to the higher anaerobic system contribution in the 100 m front crawl swim. Moreover, the known non-linear relationship between energy cost and swimming velocity indicates that minor increases in velocity leads to a substantial intensification of the energy cost (Wakayoshi et al. 1995).

As in swimming the lower limbs’ action is often considered more relevant for trunk balance, buoyancy and overall coordination than for propulsion (Gatta et al. 2012), we tested its influence over the very high swim intensity. It was possible to observe that $\dot{V}O_2$ kinetics during the S_{upper} presented a slower increase compared with the S_{full} condition as observed by the higher absolute τ values. An inverse association between $\dot{V}O_{2\text{peak}}$ and τ was identified (Zhang et al. 1991) but, when $\dot{V}O_2$ kinetics was scaled to $\dot{V}O_{2\text{peak}}$ values in each condition, the relative τ value was still higher in S_{upper} . This might be justified by the reduced cardiac output and/or a smaller arteriovenous O_2 content difference that lead to a delayed $\dot{V}O_2$ response when exercising only with the upper body (Koga et al. 1996; Pendergast 1989). This delayed increase of the oxygen delivery to the working muscles would consequently lead to higher τ values, resulting in a glycolysis increase (Koga et al. 1996), which at the beginning of effort would required more energy from anaerobic sources, compromising the fatigue tolerance in the last stages of the exercise (Jones et al. 2008).

In fact, the $\dot{V}O_{2\text{peak}}$ in S_{upper} attained only 80 % of the S_{full} condition, in accordance with the literature (Holmer 1974; Ogita 2006). Thus, the exercise intensity expressed as $\% \dot{V}O_{2\text{max}}$ could differ when using only the upper body in comparison to full body swimming, pointing out that training regimens should be developed taking into consideration these different metabolic profiles. Complementarily, the lower relative anaerobic contribution found in S_{upper} could be explained, among other factors, by the lower

muscle mass involved in the exercise (Sahlin and Henriksson 1984). It is known that enhanced lactate release is provoked by a blood-flow reduction (especially in the upper limbs) when performing full body (Secher and Volinaitis 2006). Moreover, despite swimmers performed both 100 m bouts at maximal intensity, part of the interpretation of the higher relative aerobic energy release in S_{upper} condition could also be attributed to the longer time required to cover the same distance. In addition, the S_{upper} condition was more economical (~22 %) than the S_{full} condition, most probably justified by the absence of lower limbs action (Ogita et al. 1996). Notwithstanding, it can be conjectured that lower limbs action could play an important role in the amount of aerobic energy liberated in the swimming bout, since it might enhance the acceleration of the cardiac output by decreasing the peripheral resistance for the cardiovascular system. Thus, it will enable a higher O_2 availability in all working muscles including those in the upper limbs, as suggested by the difference in τ for the condition involving lower limbs exercise or not. Moreover, it is important to note that swimming performance was ~14 % higher when using the lower limbs, a gain previously referred for high velocities, probably due to propulsion intensification and wave drag reduction (Toussaint 2011). Thus, bearing in mind that a 100 m event could be won by hundredths of a second, every added energy supply and every minimal contribution to propulsion should be exploited rather than the promotion of swimming economy by limiting lower limbs action.

As the energy pathways contribution is time dependent and since S_{full} and S_{upper} presented distinct time durations, this might be considered as a possible limitation of the present study. Although, it should be highlighted that both conditions were performed at maximal intensity, which could be interpreted as a “relative maximum”, and fulfil the objective of analysing the influence of lower limbs in 100 m front crawl energetics. Moreover, it is important to state that only one transition from rest to effort was performed in each condition, which could lead to a low signal-to-noise ratio. Nonetheless, further studies to compare the transient $\dot{V}O_2$ kinetics responses at extreme swimming intensity could be supported by the data from present study.

Conclusions

During extreme intensity swimming (100 m front crawl), an instantaneous and sudden increase of the $\dot{V}O_2$ occurred at the beginning of the exercise and continued to rise until the end of the bout, underlining the contribution of the aerobic energy pathway even in short and very intense swimming events. Nevertheless, taking into account that ~56 % of total energy was obtained anaerobically both energy

systems should be strengthened to improve the 100 m front crawl performance. Complementarily, when performing only with the upper body, the $\dot{V}O_2$ kinetics was slower, revealing the importance of the lower limbs action in providing a higher O_2 availability in all working muscles. Moreover, despite energy cost was higher to satisfy the superior energy requirements when using the lower limbs, performance improved ~14 %.

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Conflict of interest The authors declare that they have no conflict of interest.

Ethical standard The experiments were approved by the local ethics committee, and performed according to the Declaration of Helsinki.

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