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Research article

VO_2 off transient kinetics in extreme intensity swimming

Ana Sousa [1], Pedro Figueiredo [1], Kari L. Keskinen [2], Ferran A. Rodríguez [3], Leandro Machado [1], João P. Vilas-Boas [1], Ricardo J. Fernandes [1]✉
[1] Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Portugal, [2] Finnish Society of Sport Sciences, Finland, [3] National Institute of Physical Education of Catalonia (INEFC), University of Barcelona, Barcelona, Spain

Abstract

Inconsistencies about dynamic asymmetry between the on- and off-transient responses in oxygen uptake are found in the literature. Therefore, the purpose of this study was to characterize the oxygen uptake off-transient kinetics during a maximal 200-m front crawl effort, as examining the degree to which the on/off regularity of the oxygen uptake kinetics response was preserved. Eight high level male swimmers performed a 200-m front crawl at maximal speed during which oxygen uptake was directly measured through breath-by-breath oxymetry (averaged every 5 s). This apparatus was connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system. Results: The on- and off-transient phases were symmetrical in shape (mirror image) once they were adequately fitted by a single-exponential regression models, and no slow component for the oxygen uptake response was developed. Mean (± SD) peak oxygen uptake was 69.0 (± 6.3) $mL·kg^{-1}·min^{-1}$, significantly correlated with time constant of the off-transient period ($r = 0.76$, $p < 0.05$) but not with any of the other oxygen off-transient kinetic parameters studied. A direct relationship between time constant of the off-transient period and mean swimming speed of the 200-m ($r = 0.77$, $p < 0.05$), and with the amplitude of the fast component of the effort period ($r = 0.72$, $p < 0.05$) were observed. The mean amplitude and time constant of the off-transient period values were significantly greater than the respective on-transient. In conclusion, although an asymmetry between the on- and off kinetic parameters was verified, both the 200-m effort and the respectively recovery period were better characterized by a single exponential regression model.

Key words: Swimming, oxygen uptake kinetics, recovery, front crawl.

Introduction

Oxygen uptake (VO_2) kinetics has been analyzed through mathematical modeling of the constant-load exercise onset and offset VO_2 response. This response profile appears to be of an exponential nature, which could indicate first or second order kinetics operations (DiMenna and Jones, 2009). This analysis has shown that VO_2 exponentially increases at the onset of moderate exercise with constant power output (on-fast component), reaches a steady state, and rapidly decreases at the offset of moderate exercise (off-fast component) (Kilding et al., 2006; Ozyener et al., 2001; Paterson and Whipp, 1991; Scheuermann et al., 2001). First-order kinetics mandates on/off symmetry, which means that the change in VO_2 occurring when the contractile activity is ceased must be a mirror image of that which occurred when it was commenced (Rossiter et al., 2005). In the heavy intensity exercise, i.e., at intensities greater than the anaerobic threshold but below the maximal VO_2, an delayed increase (on-slow component) after the on-fast component is presented (Barstow and Molé, 1991; Barstow et al., 1996; Ozyener et al., 2001; Paterson and Whipp, 1991; Scheuermann et al., 2001), but at the offset only an off-fast component is developed (Ozyener et al., 2001; Scheuermann et al., 2001). At the severe exercise intensity, which is significantly above the anaerobic threshold, and neither VO_2 nor blood lactate levels can be stabilized (Poole et al., 1988), the on-transient VO_2 kinetics is reverted to a single-exponential profile (Ozyener et al., 2001), while the off-transient kinetics is retained for a two-component form (Dupond et al., 2010; Ozyener et al., 2001). At the highest intensity - extreme exercise leading to exhaustion before maximal oxygen uptake is attained (DiMenna and Jones, 2009; Hill et al., 2002) - , the VO_2 on-kinetics response is characterized by the development of an evident fast component, being the slow component phenomenon not developed (Burnley and Jones, 2007; Figueiredo et al., 2011; Whipp, 1994). This area of intensity was recently described (Hill et al., 2002), and, to the best of our knowledge, the VO_2 off- kinetic profile has never been studied at this particular intensity.

VO_2 assessment has been carried out mainly in well controlled environments, particularly in exercise laboratories, and the number of studies conducted in field is very scarce (Billat et al., 2002; Fernandes et al., 2008). In fact, the VO_2 off-transient kinetics is documented in constant-load exercise performed from the moderate to severe intensities. Nevertheless, studies that aim to model the VO_2 recovery kinetics at extreme intensity exercise were not yet conducted in swimming. In this sense, the purpose of this study is to characterize the VO_2 off-transient kinetics, examining also the on/off symmetry, during a 200-m front crawl maximal effort performed at extreme intensity. It was hypothesized that an on/off symmetry of the VO_2 kinetics response would be preserved, although the post-exercise VO_2 did not match the O_2 deficit.

Methods

Participants

Eight highly trained male swimmers volunteered to participate in the study. The participants provided informed written consent before data collection, which was approved by the local ethics committee and was performed

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according to the declaration of Helsinki. Their mean performance for long course 200-m freestyle was 109.3 ± 2.0 s, corresponding to 90.3 ± 3.2% of the 2009 world record for this event. This sample included a finalist and five participants at the European Championships. Individual and mean (± SD) values for subjects' main physical and performance characteristics were: age (21.8 ± 2.4 years), height (184.5 ± 6.2 cm), body mass (76.1 ± 6.5 kg), fat mass (10.4 ± 1.7%) and lean body mass (62.4 ± 4.4%).

Data collection

In an indoor 25-m swimming pool, with a water temperature of 27ºC, each swimmer performed a 200-m front crawl effort at maximal speed. In water starts and open turns, without underwater gliding, were used. Each swimmer performed a 200-m front crawl maximal effort, according to his best individual 200-m performance and his own experiences, and was encouraged to swim at his best effort; therefore, no visual or acoustic pacing was implemented. VO_2 kinetics was measured using a telemetric portable gas analyzer ($K4b^2$, Cosmed, Italy), which was connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system (Keskinen et al., 2003; Rodriguez et al., 2008), and was calibrated before and after each test. Respiratory variables were continuously monitored after the 200-m effort until baseline VO_2 values were obtained (after approximately 12 min of recovery the assessment was ended). Swimmers were advised to use continuous rhythmical breathing during swimming, turning and in the recovery period. Expired gas concentrations were measured breath-by-breath and averaged every 5 s for a better temporal resolution (Sousa et al., 2010) in order to reduce inter breath fluctuations ("noise"). Peak oxygen uptake (VO_{2peak}) was considered as the highest value of this sampling interval.

Data analysis

The following equation was used to fit VO_2 kinetics on the on-transient period:

$$\dot{V}O_2(t) = \dot{V}_b + A_{on} \times \left(1 - e^{-(t - TD_{on})/\tau_{on}}\right) \quad (1)$$

where t is the time, V_b is the oxygen uptake at the start of the exercise ($mL \cdot kg^{-1} \cdot min^{-1}$), A_{on} is the amplitude of the fast component ($mL \cdot kg^{-1} \cdot min^{-1}$), TD_{on} is the time for the onset of the fast component (s) and τ_{on} stands for the time constant of the fast component, i.e., the time to reach 63% of the plateau of this phase during which physiological adaptations adjust to meet the increased metabolic demand. The cardiodynamic phase was not taken into consideration due to its amplitude insignificant value. The inexistence of a slow component was confirmed by the rigid intervals method, particularly by the difference between the last VO_2 measurement of the exercise and the value measured in the final 5 s of the 200-m event (adapted from Fernandes et al., 2003; Koppo and Bouckaert, 2002).

For the off-transient period, the individual responses were fitted by using both a single (equation 2) and a double exponential (equation 3) regression models for the entire recovery period, in which the exponential term started at the beginning of the off-transient period modeling (TD_{1off} in the equations):

$$\dot{V}O_2(t) = A_{1off} . e^{-(t - TD_{1off})/\tau_{1off}} + A_0 \quad (2)$$

$$\dot{V}O_2(t) = A_{1off} . e^{-(t - TD_{1off})/\tau_{1off}} + A_{2off} . e^{-(t - TD_{2off})/\tau_{2off}} + A_0 \quad (3)$$

where t is the time, A_{off} represents the amplitude for the exponential term and the τ_{off} and TD_{off} are the associated time constant and time delay. A nonlinear least squares method was implemented in MatLab for the adjustment of these functions to VO_2 data.

After a visual exploratory inspection of all VO_2 curves, and for the sake of numerical stability, it was verified that, due to the extreme exercise intensity in which the 200-m held, all swimmers started the recovery period immediately after the 200-m effort. In this sense and assuming that TD_{1off}=0, the off-transient period was modeled according to the restructure equations:

$$\dot{V}O_2(t) = A_{1off} . e^{-(t/\tau_{1off})} + A_0 \quad (4)$$

$$\dot{V}O_2(t) = A_{1off} . e^{-(t/\tau_{1off})} + A_{2off} . e^{-(t - TD_{2off})/\tau_{2off}} + A_0 \quad (5)$$

Statistical analysis

For the entire sample, mean and SD computations for descriptive analysis were obtained for all variables and for the entire group of subjects, and were checked for distribution normality with the Shapiro-Wilk test. All statistical procedures were conducted with SPSS 10.05. An F-test was used to compare the single and double exponential regression models best fitting. To compare on- and off-transient parameters Paired sample T-tests were used. Simple linear regression and Pearson's correlation coefficient were computed to indicate the linear relationship between parameters and with swimming time. The level of significance was set at $p < 0.05$.

Results

The F-test (0.28) showed the homogeneity of both models variances, confirmed also by the equality of their mean values (p=0.98), and therefore, the off-transient response was well described by a single exponential function. In fact, this characterization was not improved by using the double exponential model. In this sense, the on- and off-transient periods are symmetrical in shape (mirror image) once they were adequately fitted by single-exponential functions. An example of the oxygen (O_2) uptake on and off kinetics curve is shown in Figure 1.

The mean (± SD) values for swimming speed (200_{speed}), VO_{2peak}, A_{on}, TD_{on}, τ_{on} and A_{off} and τ_{off} for the 200-m front crawl effort and recovery period are presented in Table 1.

Significant differences were obtained between the on- and off- VO_2 kinetic parameters (all for p<0.01), and its amplitude was higher in the recovery period. Complementarily to the above referred data, direct relationships were observed between τ_{off} and 200_{speed} (r = 0.77, p = 0.02), τ_{off} and VO_{2peak} (r = 0.76, p = 0.03) and τ_{off} and A_{on} (r = 0.72, p = 0.04) (see Figure 2). No significant correlations were found between VO_{2peak} and the other VO_2 off-transient parameters (A_{off}, r = 0.35, for p > 0.05). The absences of significant relationships were also observed between τ_{on} and τ_{off} (r = 0.19) and A_{on} and A_{off} (r = 0.5), all with p > 0.05.

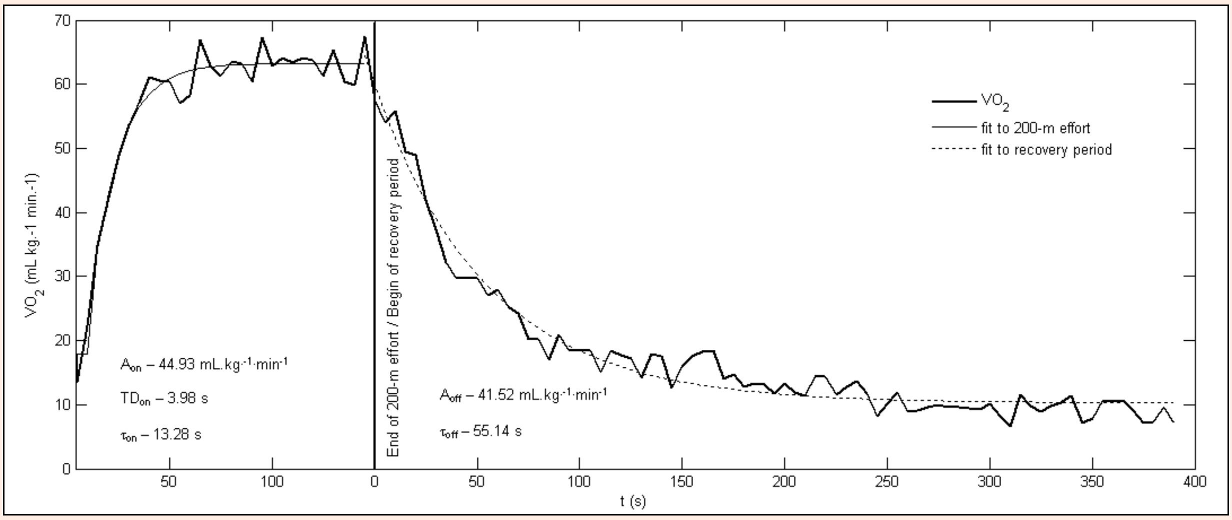

Figure 1. Example of an oxygen consumption to time curve, being the time of the onset of the fast component (TD_{on}), the time constant of the fast component (τ_{on}) and the amplitude of the fast component (A_{on}) in the on-transient and off-transient (τ_{off}, A_{off}) periods identified.

Discussion

The aim of this study was to characterize the VO_2 off-transient kinetics and to examine the on/off symmetry during a self-imposed 200-m swimming at race pace. We tested the hypothesis that the VO_2 kinetics response will manifest a symmetric on/off response, even if the post-exercise VO_2 does not match the O_2 deficit.

An understanding of the VO_2 kinetics is considered an important parameter to improve sports training methodology and increase performance in sport (Billat et al., 2001). Furthermore, it was recently suggested that the determinants of exercise tolerance and the limitations to sports performance can be better understood through an appreciation of the physiological significance of the fast and slow components of the dynamic VO_2 response to exercise (Burnley and Jones, 2007). For a long time, studies regarding O_2 uptake assessment in swimming were conducted with either Douglas bags (di Prampero et al., 1974; Lavoie and Montpetit, 1986) or mixing chamber gas analyzers (Dal Monte et al., 1994; Demarie et al., 2001). It was only recently that the development of a swimming snorkel suitable for breath-by-breath analysis (Keskinen et al., 2003; Rodríguez et al., 2008) allowed assessing VO_2 dynamics in swimming pool conditions through direct oxymetry (Fernandes et al., 2003; Rodriguez et al., 2003). Nevertheless, in the O_2 uptake kinetics related literature, studies that aimed to characterize it in human non-constant load extreme intensity exercises are very scarce. Moreover, among these studies, only Rodriguez and Mader (2003), Rodriguez et al. (2003), and Silva et al. (2006) implemented a swimming effort at intensities similar to our protocol.

Considering the total sample, VO_{2peak} ranged from 60.2 to 81.8 $ml \cdot kg^{-1} \cdot min^{-1}$, which is in accordance with recently reported data obtained in trained male competitive swimmers performing during swimming in pool conditions (Fernandes et al., 2008; Figueiredo et al., 2011; Reis et al., 2010; Rodríguez and Mader, 2003; Rodríguez et al., 2003; Silva et al., 2006).

Table 1. Individual, mean (± SD) values, coefficient of variation and confidence interval for mean for 200_{speed}, VO_{2peak}, A_{on}, TD_{on} and τ_{on}, A_{off} and τ_{off} in the 200-m maximal effort and recovery period.

Swimmer	200_{speed} ($m \cdot s^{-1}$)	VO_{2peak} ($mL \cdot kg^{-1} \cdot min^{-1}$)	A_{on} ($mL \cdot kg^{-1} \cdot min^{-1}$)	TD_{on} (s)	τ_{on} (s)	A_{off} ($mL \cdot kg^{-1} \cdot min^{-1}$)	τ_{off} (s)
#1	1.40	68.4	49.6	10.00	6.21	54.4	62.22
#2	1.36	60.2	38.6	4.99	12.04	41.2	49.38
#3	1.44	67.4	44.9	3.98	13.28	41.5	55.14
#4	1.42	70.7	44.5	4.99	9.31	54.8	73.13
#5	1.49	81.8	52.0	5.00	12.43	50.1	94.04
#6	1.42	70.1	45.4	4.99	11.56	49.3	84.36
#7	1.42	63.7	46.9	4.99	9.17	42.2	73.90
#8	1.47	69.0	50.2	4.99	13.41	62.3	86.23
Mean (±SD)	1.42 (.04)	69.0 (6.3)	46.5 (4.2)	5.49 (1.85)	10.92 (2.49)	49.5 (7.56)	72.30(15.75)
CV mean	2.81%	9.13%	9.05%	33.69%	22.84%	15.27%	21.78%
CI mean	1.39-1.46	63.7-74.3	43.0-50.0	3.93-7.04	8.84-13.01	43.2-55.8	59.13-85.46

200_{speed} = mean swimming speed of the 200-m; VO_{2peak} = peak oxygen uptake; A_{on} = amplitude of the fast component in the 200-m maximal effort; TD_{on} = time of the onset of the fast component in the 200-m maximal effort; τ_{on} = time constant of the fast component in the 200-m maximal effort; A_{off} = amplitude of the fast component in the 200-m recovery period; τ_{off} = time constant of the fast component in the 200-m recovery period; CV = coefficient of variation; CI = confidence interval.

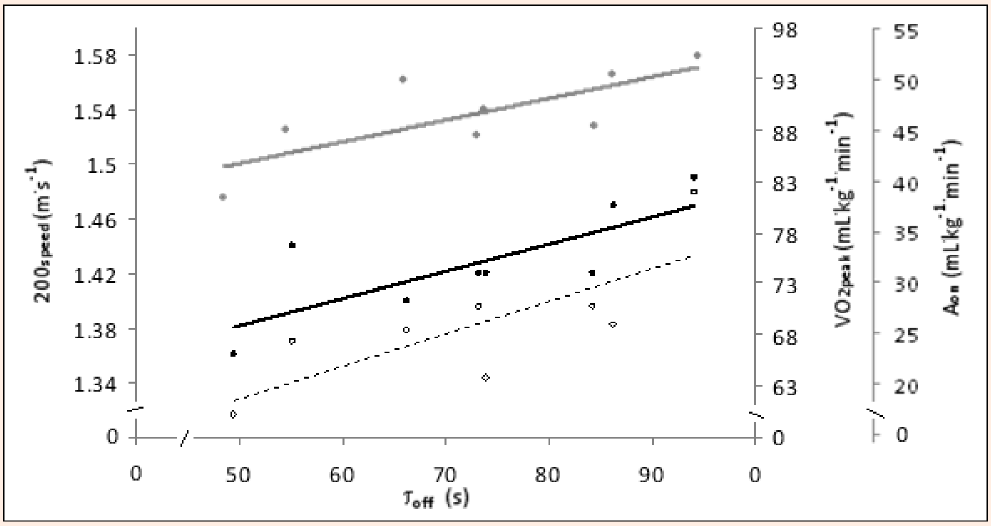

Figure 2. Relationships between the time constant of the fast component of the recovery period (τ_{off}) and the mean swimming speed of the 200-m (200_{speed} - full line: y =1.284x + 0.002, n = 8, r = 0.77, p < 0.05), between τ_{off} and peak oxygen uptake (VO_{2peak} - dotted line: y = 46.975x + 0.305, n = 8, r = 0.76, p < 0.05) and between τ_{off} and the amplitude of the fast component of the effort period (A_{on} - grey line: y= 32.594x + 0.192, n = 8, r = 0.72, p < 0.05).

Symmetry between the on- and off-transient phases: Since symmetry is an essential quality of VO_2 kinetic dynamics viewed as a first-order reaction kinetics (Rossiter et al., 2005), it was a focus of interest in the present study. The on/off symmetry of the fast components has been observed for the moderate intensity exercise domain performed in cycle ergometer (Paterson and Whipp, 1991; Ozyener et al., 2001; Scheuermann et al., 2001) and treadmill running (Kilding et al., 2006). For the heavy intensity exercise, an asymmetry in the VO_2 dynamics has been reported, describing an on-fast component and an off-fast and off-slow components at cycle ergometer (Ozyener et al., 2001) and knee extensor exercise (Rossiter et al., 2002). This asymmetry was also reported for severe exercise intensity, namely in indoor running (Dupond et al., 2010) and cycle ergometer (Ozyener et al., 2001). In contrast, in the present study the on- and off-transient phases were symmetrical, once they were adequately fitted by a single exponential function, compared to the double exponential one, and no slow component for the VO_2 response was developed (see Figure 1). Nonetheless the above referred studies, the symmetry observed in the present study can be explained by the implementation of a non-constant load, and to the greater exercise intensity. As expected, we observed only an on-fast component, since the non-constant load at freely-chosen maximal race pace induced an exponential rise in VO_2 kinetics that unable the development of a VO_2 slow component; this fact was previously mentioned but only for ergometer exercise (Burnley and Jones, 2007; Whipp, 1994).

On/off kinetic parameters: Although an on/off symmetry in the VO_2 kinetic response was observed in this extreme intensity exercise lasting 2.7 min on average, differences between the VO_2 on- and off-transient kinetic parameters were observed. In fact, greater A_{off} and τ_{off} values are reported. This last parameter is a major focus of interest in the VO_2 kinetic related literature, once it is a determinant factor in VO_2 dynamics. A longer τ_{off} value, as observed in this study, concur with previous data obtained in the heavy exercise domain (Cleuziou et al., 2004; Yano et al., 2007); however, other studies reported the opposite behavior for the same exercise intensity (Engelen et al., 1996; Ozyener et al., 2001; Scheuermann et al., 2001), as well as for the moderate domain (Patterson and Whipp, 1991). At the severe exercise intensity, Billat et al. (2002) and Ozyener et al. (2001) reported no differences in τ regarding on and off fast periods. In addition, the obtained τ_{off} mean value was greater than the results reported in the literature for both moderate (Cleuziou et al., 2004; Kilding et al., 2006; Rossiter et al., 2002; Takayoshi et al., 2003), heavy (Rossiter et al., 2002) and severe intensities (Perrey et al., 2002).

However, as suggest, when we compared our data with studies using a double exponential fitting approach, τ_{off} was shorter comparing to τ_{off} of the slow component during heavy (Cleuziou et al., 2004) and severe intensity exercise (Dupond et al., 2010). As previously stated, the present study reported a symmetry on the on/off VO_2 kinetic response; however differences between the on- and off- VO_2 kinetic related parameters were found.

In fact, VO_2 kinetics is influenced by endurance training, being reported a faster VO_2 on-kinetics in trained subjects involved both in cross-sectional and longitudinal studies (Casaburi et al., 1987; Koppo et al., 2004; Murias et al., 2010; Phillips et al., 1995). Indeed, training seems to change the muscle fiber-type characteristics, mitochondrial density, oxidative enzyme activity, oxygen availability, capillary density and muscle perfusion (Koppo et al., 2004), existing evident differences between trained and untrained subjects. Although this study did not have the intention to investigate this phenomenon, the mean swimming speed was very high since the onset of the effort, which may induced a faster increase in ATP requirements, and a fast lactate accumulation, once a pattern of type I/II muscle fiber contribution seems to be established without delay (Cunningham et al., 2000). These facts (and being the off-set fast component explained by the restore of O_2 in blood and in muscle, a significant lactate removal, and by the resynthesis of ATP and PCr) may induce discernible slower responses during the recovery period. Hence, the oxygen debt must be larger than the oxygen deficit, i.e., the post-exercise VO_2 quantitatively did not match the O_2 deficit (Yano et al., 2007). In fact, since different pacing strategies were adopted during the maximal 200-m, different VO_2 on kinetics may occurred, which influenced the VO_2 response in the recovery period. This is a limitation of the current study comparing to constant pace researches.

Regarding the VO_2 amplitude, the greater observed A_{off} mean value (comparing to A_{on}) is not in accordance with the results reported for moderate and heavy intensities (Cleuziou et al., 2004), and for the severe intensity exercise (Perrey et al., 2002), that showed no significant differences between the A_{on} and A_{off} mean values. In our study, the greater values of A_{off} may be a result of the extreme exercise intensity in which our study was conducted, different modeling procedures that were used, as also mode of exercise performed. At this exercise intensity, in which highest work rates are observed, the VO_2 mean value is high even until the end of the effort. Once the A_{off} represents the difference between the VO_2 at the end of the exercise and the steady state VO_2, the greater A_{off} mean value seems justified.

Once the TD_{off} was assumed to be zero, in result of the sudden and instantaneous diminishing of VO_2, comparisons with previously reported data obtained for the moderate (Cleuziou et al., 2004) and heavy intensities domains (Billat et al., 2002) are difficult to establish. However, Takayoshi et al. (2003) reported low TD_{off} mean values (1, 2 s) for the moderate exercise intensity domain. Moreover, and contrasting the results of the present study, Perrey et al. (2002) found no differences between the TD_{on} and TD_{off} mean values at severe intensity.

Relationship between VO_2 kinetics on/off-transient phases and performance: The observed direct relationship between τ_{off} and 200_{speed} evidences that the swimmers who performed a faster 200-m, needed more time to attained a VO_2 steady state in the off-transient phase; in addition, these swimmers presented greater VO_{2peak} and A_{on} mean values. These facts seem to evidence one more time that the very high swimming speed just after the beginning of the effort led to greater VO_{2peak} and A_{on} mean values, increasing both the need for a higher energy supply and the accumulation of fatigue-related metabolites, slowing the recovery phase. Indeed, the 200-m performance is strongly related to the τ_{off}, which seems to be also a good predictor of VO_{2peak} and A_{on}. However, these data should be seen with precaution, once other factors might explain the performance variability in this specific distance.

Conclusion

No slow component for the VO_2 off-kinetics was developed in the all-out 200-m swims, and the on and off-transient phases were symmetrical once they were adequately fitted by a single-exponential function. However, A_{off} and τ_{off} mean values were greater comparing to the respective on-transients parameters. The VO_{2peak} and 200_{speed} mean values positively correlated with τ_{off}, as this with A_{on}, not being observed any more correlations between any of the studied on/off-transient kinetic parameters. Accepting that the overall understanding of the VO_2 kinetics implies the address of other research areas, future experiments are welcome to understand the underlying mechanism regarding this VO_2 dynamic behavior.

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References

Barstow, T. and Molé, P. (1991) Linear and nonlinear characteristics of oxygen uptake kinetics during heavy exercise. *Journal of Applied Physiology* **71(6),** 2099-2106.

Barstow, T., Jones, A., Nguyen, P. and Casaburi, R. (1996) Influence of muscle fiber type and pedal frequency on oxygen uptake kinetics of heavy exercise. *Journal of Applied Physiology* **81(4),** 1642-1650.

Billat, V., Hamard, L. and Koralsztein, JP. (2002) The influence of exercise duration of the VO_2max on the off-transient pulmonary oxygen uptake phase during high intensity running activity. *Archives of Physiology and Biochemistry* **110(5),** 383-392.

Billat, VL. (2001) Interval training for performance: A scientific and empirical practice. Special recommendations for middle and long distance running. Part I: Aerobic interval training. *Sports Medicine* **31(1),** 13-31.

Burnley, M. and Jones, A. (2007) Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sport Science* **7(2),** 63-79.

Casaburi, R., Storer, TW., Ben-Dov, I. and Wasserman, K. (1987) Effect of endurance training on possible determinants of VO_2 during heavy exercise. *Journal of Applied Physiology* **62(1),** 199-207.

Cleuziou, C., Perrey, S., Borrani, F., Lecoq, A., Candau, R., Courteix, D. and Obert, P. (2004) Dynamic responses of oxygen uptake and end of moderate and heavy exercise in trained subjects. *Canadian Journal of Applied Physiology* **29(1),** 32-44.

Cleuziou, C., Perrey, S., Lecoq, M., Candau, R., Courteix, D. and Obert, P. (2005) Oxygen uptake kinetics during moderate and heavy intensity exercise in humans: the influence of hypoxia and training status. *International Journal of Sports Medicine* **26(5),** 356-62.

Cunningham, D., Croix, D., Ozyener, J. and Whipp, B. (2000) The off-transient pulmonary oxygen uptake (VO2) kinetics following attainment of a particular VO2 during heavy-intensity exercise in humans. *Experimental Physiology* **85,** 339-347.

Dal Monte, A., Sardelle, F., Alippi, B., Faina, M. and Manetta, A. (1994) Anew respiratory valve system for measuring oxygen uptake during swimming. *European Journal of Applied Physiology* **69(2),** 159-162.

Demarie, S., Sardella, F., Billat, V., Magini, W. and Faina, M. (2001) The VO_2 slow component in swimming. *European Journal of Applied Physiology* **84(1-2),** 95-99.

DiMenn,a FJ. and Jones, A. (2009) "Linear" versus "Nonlinear" VO_2 responses to exercise: reshaping traditional beliefs. *Journal of Exercise and Science Fitness* **7(2),** 67-84.

Di Prampero, P.E., Pendergast, D.R., Wilson, D.W. and Rennie, D.W. (1974) Energetics of swimming in man. *Journal of Applied Physiology* **37(1),** 1-5.

Dupond, G., McCall, A., Prieur, F., Millet, G. and Berthoin, S. (2010) Faster oxygen uptake kinetics during recovery is related to better repeated sprinting ability. *European Journal of Applied Physiology* **110,** 627-634.

Engelen, M., Porszasz, J., Riley, M., Wasserman, K., Maehara, K. and Barstow, T. (1996) Effects of hypoxic hypoxica on O_2 uptake and heart rate kinetics during heavy exercise. *Journal of Applied Physiology* **81,** 2500-2508.

Fernandes, RJ., Cardoso, CS., Soares, SM., Ascensão, A., Colaço, P. and Vilas-Boas, JP. (2003) Time limit and VO2 slow component at

intensities corresponding to VO2max in swimmers. *International Journal of Sports Medicine* **24(8),** 576-581.
Fernandes, R., Keskinen, K., Colaço, P., Querido, A., Machado, L., Morais, P., Novais, D., Marinho, D. and Vilas Boas, JP. (2008) Time limit at VO2max velocity in elite crawl swimmers. *International Journal of Sports Medicine* 29, 145-150.
Fernandes, R., Sousa, A., Figueiredo, P., Keskinen, K., Rodriguez, F., Machado, L. and Vilas-Boas, J. (2011) Modeling off-transient oxygen uptake kinetics after maximal 200-m swims, *Medicine and Science in Sports and Exercise* **43(5), S264.**
Figueiredo, P., Zamparo, P., Sousa, A., Vilas Boas, J.P. and Fernandes, R. (2011) An energy balance of the 200 m front crawl race. *European Journal of Applied Physiology* **111,** 767-777.
Hill, D.W., Poole, D.C. and Smith, C. (2002) The relationship between power and the time to achieve VO_{2max}. *Medicine and Science in Sports and Exercise* **34,** 709-714.
Keskinen, K., Rodriguez, O. and Keskinen, O. (2003) Respiratory snorkel and valve system for breath-by-breath gas analysis in swimming. *Scandinavian Journal of Medicine and Science in Sport* **13(5),** 322-329.
Kilding, A., Winter, EM. and Fish, M. (2006) A comparison of pulmonary oxygen uptake kinetics in Middle- and Long-Distance Runners. *International Journal of Sports Medicine* **27(5),** 419-426.
Koga, S., Shiojiri, T. and Kondo, N. (2005) Measuring VO2 kinetics: The practicalities. In: *Oxygen Uptake Kinetics in Sport, Exercise and Medicine*. Eds: Jones, A.M. and Poole, D.C. Routledge, London & New York: 39-61.
Koppo, K. and Bouckaert, J. (2002) The decrease in the VO_2 slow component induced by prior exercise does not affect the time to exhaustion. *International Journal of Sports Medicine* **23,** 262-267.
Koppo. K., Bouckaert, J. and Jones, AM, (2004) Effects of training status and exercise intensity on phase II VO_2 kinetics. *Medicine and Science in Sport and Exercise* **36(2),** 225-232.
Lavoie, J.M. and Montpetit, R.R. (1986) Applied physiology of swimming. *Sports Medicine* **3(3),** 165-189.
Murias, J.M., Kowalchuck, J.M. and Paterson, D.H. (2010) Speeding of VO_2 kinetics with endurance training in old and young men is associated with improved matching of local O_2 delivery to muscle O_2 oxygenation. *Journal of Applied Physiology* **108(4),** 913-922.
Ozyener, F., Rossiter, H., Ward, S. and Whipp, B. (2001) Influence of exercise intensity on the on and off-transient kinetics of pulmonary oxygen uptake in humans. *Journal of Physiology* **533(3),** 891-902.
Paterson, D. and Whipp, B. (1991) Asymmetries of oxygen uptake transients at the on- and offset of heavy exercise in humans. *Journal of Physiology* **443,** 575-586.
Perrey, S., Candau, R., Borrani, F., Millet, G. and Rouillon, J. (2002) Recovery kinetics of oxygen uptake following severe-intensity exercise in runners. *Journal of Sports Medicine and Physical Fitness* **42(4),** 381-388.
Phillips, S.M., Green, H.J., MacDonald, M.J. and Hughson, R.L. (1995) Progressive effect of endurance training on VO_2 kinetics at the onset of submaximal exercise. *Journal of Applied Physiology* **79(6),** 1914-1920.
Poole, D.C., Ward, S.A., Gardner, G.W. and Whipp, B.J. (1988) Metabolic and respiratory profile of the upper limit for prolonged exercise in man. *Ergonomics* **31,** 1265-1279.
Reis, V., Marinho, D., Policarpo, F., Carneiro, A., Baldari, C. and Silva, A. (2010). Examining the accumulated oxygen deficit method in front crawl swimming. *International Journal of Sports Medicine* **31(6),** 421-427.
Rodriguez, F. and Mader, A. (2003) Energy metabolism during 400m and 100m crawl swimming: computer simulation based on free swimming measurement. In: *IX Biomechanics and Medicine in Swimming*. Eds: Chatard, J.E. Publications de l'Université de Saint-Étienne: 373-378.
Rodriguez, F.A., Keskinen, K.L., Keskinen, O.P. and Malvela, M. (2003) Oxygen uptake kinetics during free swimming: a pilot study. In: *IX Biomechanics and Medicine in Swimming* Eds: Chatard, J. E. Publications de l'Université de Saint-Étienne: 379-384.
Rodriguez, F.A., Keskinen, K.L., Kusch, M. and Hoffmann, U. (2008) Validity of a swimming snorkel for metabolic testing. *International Journal of Sports Medicine* **29(2),** 120-128.
Rodriguez, F.A. (2000) Maximal oxygen uptake and cardiorespiratory response to maximal 400-m free swimming, running and cycling tests in competitive swimmers. *Journal of Sports Medicine and Physical Fitness* **40(2),** 87-95.
Rossiter, H.B., Howe, F.A. and Ward, S.A. (2005) Intramuscular phosphate and pulmonary VO_2 kinetics during exercise: implications for control of skeletal muscle oxygen consumption. In: *Oxygen Uptake Kinetics in Sport, Exercise and Medicine*. Eds: Jones, A.M. and Poole, D.C. Routledge, London & New York: 154-184.
Rossiter, H., Ward, S., Kowalchuk, J., Howes, F., Griffiths, J. and Whipp, J. (2002) Dynamic asymmetry of phosphocreatine concentration and O2 uptake between the on- and off-transients of moderate and high-intensity exercise in humans. *Journal of Physiology* **541(3),** 991-1002.
Scheuermann, B., Hoelting, B., Noble, M. and Barstow, T. (2001) The slow component of O2 uptake is not accompanied by changes in muscle EMG during repeated bouts of heavy exercise in human. *Journal of Physiology* **531,** 245-256.
Short, K. and Sedlock, D. (1997) Excess post exercise oxygen consumption and recovery rate in trained and untrained subjects. *Journal of Applied Physiology* **83(1),** 153-159.
Silva, A., Reis, V., Reis, A., Garrido, N., Moreira, A., and Carneiro, A. (2006) Associations between energy release and performance in a supramaximal effort of 200-m in crawl. *Portuguese Journal of Sport Science* **6(Suppl.1),** 59-60.
Sousa, A., Figueiredo, P., Oliveira, N., Keskinen, K., Vilas-Boas, J.P. and Fernandes, R. (2010). Comparison between VO_2peak and VO_2max at different time intervals. *Open Sport Science Journal* **3,** 22-24.
Takayohi, Y., Yamamoto, K., Naka, T. and Udo, M. (2003) Cardiac output and oxygen uptake kinetics at the onset and offset of exercise. *Journal of Thermal Biology* **18(5-6),** 609-615.
Whipp, B. (1994) The slow component of O_2 uptake kinetics during heavy exercise. *Medicine and Science in Sports and Exercise* **26,** 1319-1326.
Yano, T., Yunoki, T., Matsura, R., Arimitsu, R. and Kimura, T. (2007) Excessive Oxygen Uptake during Exercise and Recovery in Heavy Exercise. *Physiology Research* **56,** 721-725.

Key points

- The VO_2 slow component was not observed in the recovery period of swimming extreme efforts;
- The on and off transient periods were better fitted by a single exponential function, and so, these effort and recovery periods of swimming extreme efforts are symmetrical;
- The rate of VO_2 decline during the recovery period may be due to not only the magnitude of oxygen debt but also the VO_{2peak} obtained during the effort period.

AUTHORS BIOGRAPHY

Ana SOUSA
Employment
FCT research assistant. Sport Sciences PhD student. Collaborator of the Centre of Research, Education, Innovation and Intervention in Sport.
Degree
MSc on Sport Sciences.
Research interests
Physiology applied to swimming, swimming training.
E-mail: sousa.acm@gmail.com

Pedro FIGUEIREDO
Employment
FCT research assistant. Sport Sciences PhD student. Collaborator of the Centre of Research, Education, Innovation and Intervention in Sport.
Degree
Graduation on Sport Sciences.
Research interests
Biomechanics and physiology applied to swimming, triathlon training.
E-mail: spafg@vodafone.pt

Kari KESKINEN
Employment
Executive Director at Finnish Society of Sport Sciences. Professor, Researcher, Lecturer at University of Jyväskylä.
Degree
PhD
Research interests
Physiological evaluation applied to swimming.
E-mail: kari.keskinen@lts.fi

Ferran RODRIGUEZ
Employment
Medical Doctor at the Department of Health and Applied Sciences of the University of Barcelona.
Degree
PhD, MD
Research interests
Physiological evaluation applied to swimming.
E-mail: farodriguez@gencat.cat

Leandro MACHADO
Employment
Auxiliary Professor at the Porto University. Member of Centre of Research, Education, Innovation and Intervention in Sport.
Degree
PhD
Research interests
Mathematical approach applied to swimming.
E-mail: lmachado@fade.up.pt

João Paulo VILAS-BOAS
Employment
Full Professor, Head of the Biomechanics Lab at the Porto University. Member of the Scientific Committee of Centre of Research, Education, Innovation and Intervention in Sport.
Degree
PhD on Sport Sciences.
Research interests
Biomechanics, exercise physiology applied to swimming.
E-mail: jpvb@fade.up.pt

Ricardo J. FERNANDES
Employment
Auxiliary Professor, Head of the Swimming Department at the Porto University. Member of Centre of Research, Education, Innovation and Intervention in Sport.
Degree
PhD on Sport Sciences.
Research interests
Swimming biophysical characterization specially centered on the availability and use of energy.
E-mail: ricfer@fade.up.pt

✉ **Ricardo J. Fernandes**
Faculty of Sport, University of Porto, Rua Plácido Costa, 91, 4200, Portugal