Oxygen uptake kinetics and middle distance swimming performance

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Abstract

The aim of this study was to determine whether \( \dot{V}O_2 \) kinetics and specifically, the time constant of transitions from rest to heavy (\( \tau_p^H \)) and severe (\( \tau_p^S \)) exercise intensities, are related to middle distance swimming performance. Fourteen highly trained male swimmers (mean ± SD: 20.5 ± 3.0 years; 75.4 ± 12.4 kg; 1.80 ± 0.07 m) performed a discontinuous incremental test, as well as square wave transitions for heavy and severe swimming intensities, to determine \( \dot{V}O_2 \) kinetics parameters using two exponential functions. All the tests involved front-crawl swimming with breath-by-breath analysis using the Aquatrainer swimming snorkel. Endurance performance was recorded as the time taken to complete a 400 m freestyle swim within an official competition (T400), one month from the date of the other tests. T400 (mean ± SD) (251.4 ± 12.4 s) was significantly correlated with \( \tau_p^H \) (15.8 ± 4.8 s; \( r = 0.62; p = 0.02 \)) and \( \tau_p^S \) (15.8 ± 4.7 s; \( r = 0.61; p = 0.02 \)). The best single predictor of 400 m freestyle time, out of the variables that were assessed, was the velocity at \( \dot{V}O_2 \) max (\( \nu \dot{V}O_2 \) max), which accounted for 80% of the variation in performance between swimmers. However, \( \tau_p^H \) and \( \dot{V}O_2 \) max were also found to influence the prediction of T400 when they were included in a regression model that involved respiratory parameters only. Faster kinetics during the primary phase of the \( \dot{V}O_2 \) max response is associated with better performance during middle-distance swimming. However, \( \nu \dot{V}O_2 \) max appears to be a better predictor of T400.

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1. Introduction

Competitive middle distance swimming involves abrupt transitions from rest to high intensity exercise. Successful coping with the rapid increase in energetic demand that is involved requires a high level of coordination between the cardiorespiratory and muscular systems. In the transition from rest to moderate intensity exercise, and after a short delay (‘cardiodynamic’ phase), the oxygen uptake response follows an exponential profile. The time constant (\( \tau_p \)) completion of 63% of this “primary response” is usually 20–35 s, such that steady state is attained within 2–3 min.1 During constant-load exercise above the first ventilatory threshold, a \( \dot{V}O_2 \) slow component is superimposed on to the primary phase. This slow component can delay the attainment of steady state \( \dot{V}O_2 \) by 15–20 min during (“heavy”) exercise below the athlete’s critical power (CP). During (“severe”) exercise above CP, \( \dot{V}O_2 \) continues to rise until the athlete’s maximal oxygen uptake \( \dot{V}O_2 \) max or fatigue is reached.1

Previous studies have reported that faster \( \dot{V}O_2 \) kinetics and reduced amplitude of the slow component are highly correlated with higher levels of aerobic fitness,2 improved training status,3 and better tolerance of fatigue.4,5 Additionally, \( \tau_p \) has been shown to be significantly correlated with performance times in endurance cycling, running and rowing.6–8 For example, Kilding et al.7 reported shorter \( \tau_p \)’s (i.e. faster \( \dot{V}O_2 \) kinetics) to be associated with faster 5-km performance times in 36 trained male runners.

To date, however, studies investigating the relationship between aerobic power or economy, and swimming performance, have had equivocal results. Some researchers9 have observed significant correlations to exist between \( \dot{V}O_2 \) max and swimming performance, whilst others10 have not. Swimming economy appears to be a better predictor of swimming performance than \( \dot{V}O_2 \) max, particularly in the case of middle distance swimming. However, \( \nu \dot{V}O_2 \) max appears to be a better correlate of swimming performance.
distance events. As both aerobic power and economy are related to \( \dot{V}O_2 \) kinetics, \( \dot{V}O_2 \) kinetics parameters may be useful indices of performance. It is known that endurance training has important effects on the fundamental component of the \( \dot{V}O_2 \) kinetics. A reduction in the amplitude of this response would signify an improved exercise economy/efficiency, but effects on the time constant of the response are even more profound. In addition, decrease in the amplitude of the slow component leads to a proportional increase in economy. This might be particularly important for exercise above the critical power. Furthermore, the enhanced exercise tolerance that attends endurance training has been related to changes in both the “fast” and “slow” components of the \( \dot{V}O_2 \) kinetics response.

Unfortunately, limited description of the \( \dot{V}O_2 \) kinetics response to constant load swimming exercise exists in the literature. To our knowledge, only one study to date has described the time constant of the primary phase. The relationship between the \( \dot{V}O_2 \) response at two different sub-maximal intensities and performance has yet to be clarified. It is possible that constraints in blood flow/oxygen transport and/or greater respiratory work during swimming could be responsible for important differences in \( \dot{V}O_2 \) kinetics from those that have been reported for upright exercise.

The purpose of this study, therefore, was to determine the extent to which \( \dot{V}O_2 \) kinetics parameters measured during square-wave transitions from rest to high-intensity swimming exercise are related to middle distance swimming performance. We chose the 400 m freestyle event because it normally involves both a significant aerobic and anaerobic component.

Specifically, we hypothesised that (1) \( r_P \) and the amplitude of the \( \dot{V}O_2 \) slow component during heavy or severe rest-exercise transitions would be significantly and positively correlated with 400 m freestyle time; and that (2) both parameters could be integrated into a regression model to successfully predict 400 m freestyle time.

2. Methods

Fourteen highly trained, National level, male swimmers (mean ± SD: 20.5 ± 3.0 years; 75.4 ± 12.4 kg; 1.80 ± 0.07 m) gave their written informed consent to participate in the study. The study was approved by the local University Ethical Committee and conducted in accordance with the 1975 Declaration of Helsinki. All study participants had regularly competed at National Championship level for at least the 5 year period leading up to the study, and trained at least 8 times per week. Moreover, all the swimmers were frequent participants in experimental studies undertaken by our research group, and, as such, were fully familiarised with the test procedures and equipment that were used, prior to the study onset.

The study was timed to coincide with the beginning of the preparatory period of the second macro-cycle of the swimmer’s competitive season. Each swimmer performed 3 testing sessions, separated by at least 24 h rest, over a 10 day period, as explained below. The same environmental conditions, time of day and pre-test warm up applied to all tests. All tests involved in-water starts and open turns without underwater gliding, and all took place in the same indoor 50 m pool. The swimmers adjusted their speed within each test to that prescribed by the first investigator, on the basis of acoustic feedback, at every 25th metre. If the difference between the prescribed and the attained velocity was superior to 0.01 m s\(^{-1}\), the test was interrupted and repeated after a 1 h rest. This was the case for only one swimmer. Cardiorespiratory analysis of expired air was performed during all tests, using a breath-by-breath analyser (K4b\(^2\), Cosmed, Italy). The K4b\(^2\) was calibrated prior to each test according to the manufacturer’s instructions before being connected to the swimmer by a previously validated respiratory snorkel and valve system (Aquatrainer, Cosmed, Italy). The temperature of the flowmeter was also set to ambient temperature, in accordance with the manufacturer’s instructions.

The swimmers first performed a discontinuous incremental test (comprising 5 × 200 m with 30 s rest intervals) to voluntary exhaustion, for determination of both the ventilatory threshold (VT) and maximal oxygen uptake (\( \dot{V}O_2 \)max). The speed of the first repetition was calculated as 60% of the subject’s 200 m personal best velocity. Five to ten percent increments in speed were imposed between each consecutive 200 m repetition, such that the fifth and final repetition was performed at maximal speed. The velocity associated with \( \dot{V}O_2 \)max (\( \dot{V}O_2 / \dot{V}O_2 \)) was determined as the minimal velocity at which \( \dot{V}O_2 \)max was elicited, and was always attained in the last repetition. \( \dot{V}O_2 \)max was recorded as the highest 30 s average of oxygen uptake values. VT was established as the oxygen uptake at which VE/\( \dot{V}O_2 \) and end-tidal \( O_2 \) pressure (PET\( O_2 \)) began to increase without a simultaneous increase in end-tidal \( CO_2 \) pressure (PET\( CO_2 \)). Heart rate at the end of the exercise bout (End-exercise HR) was recorded telemetrically (Polar RS 800, Kempele, Finland). Fingertip blood lactate concentration was determined immediately after each repetition, as well as 3, 5 and 7 min after the end of the exercise bout, using the Lactate Pro portable analyser (Arkay, Kyoto, Japan). The maximal lactate concentration (L\( a \)max) was determined as the highest lactate value registered.

On subsequent days, the swimmers performed three 6-min constant velocity swimming bouts corresponding to 80% VT, to 25%\( \Delta \) [VT + 0.25(\( \dot{V}O_2 \)max – VT)] (H) and to 70%\( \Delta \) (S), respectively. The first two bouts were separated by 6 min of passive rest. One hour of passive rest was then taken between H and S. According to Burnley et al., these inter-bout rest times ensured that previous heavy exercise do not influence the \( \dot{V}O_2 \) kinetics of subsequent exercise bouts.

The above procedure was repeated by all the swimmers within one week of its first completion. Thus, \( \dot{V}O_2 \) kinetics data were obtained for a total of two 80% VT, two H, and two S exercise transitions.
The breath-by-breath data from each square wave transition were first cleaned by exclusion of values lying more than three standard deviations from the local mean.

The data of the two square-wave transitions for H and S swimming were then interpolated into 1-s values, time-aligned, and ensemble averaged to provide a single transient set of data for each swimming transition.

To remove the influence of the cardio-dynamic phase on the subsequent VO2 response we further chose to remove the first 20 s of data from the analysis. We further calculated an individual “snorkel delay” (ISD) for each subject repetition. The ISD (which corresponded to the difference between the onset of exercise (t0) and the time (tISD) when the following breaths summed a tidal volume (TV) superior to the outlet tube volume (RSV)) was then integrated into the time delay of the primary phase, as described by Reis et al.17

We modelled the VO2 kinetics according to Eq. (1):

$$VO2(t) = \begin{cases} 
\text{VO2}_\text{base} + A_p(1 - e^{-(t-tdp)/\tau_p}) 
& \text{for } t < tdp \\
\text{VO2}_\text{base} + A_p(1 - e^{-(tdc-tdp)/\tau_p}) + A_{sc}(1 - e^{-(t-tdc)/\tau_{sc}}) 
& \text{for } tdp \leq t < tdc \\
\text{VO2}_\text{base} + A_p(1 - e^{-(tdc)/\tau_p}) + A_{sc}(1 - e^{-(t-tdc)/\tau_{sc}}) 
& \text{for } t \geq tdc
\end{cases}$$

where $VO2(t)$ represents the relative VO2 at a given time, $VO2_{\text{base}}$ represents the rest VO2 (which itself was calculated as the average VO2 of the first 30 s of the last minute before the start of the exercise), $tdp$, $\tau_p$, $A_p$ represent the time delay, the time constant and the amplitude of the primary phase and slow component, respectively; and $tdc$, $\tau_{sc}$, $A_{sc}$, represent the equivalent parameters for the slow component. Because the asymptotic value of the second function is not necessarily reached at the end of the exercise, the amplitude of the VO2 slow component was defined as

$$A'_{sc} = A_{sc}(1 - e^{-(t-tdc)/\tau_{sc}})$$

where VO2 was the time at the end of the exercise bout.20

VO2 kinetics parameters were calculated, by an iterative procedure, by minimising the sum of the mean squares of the differences between the modelled and the measured VO2 values.

Swimming economy was determined as the ratio between end-exercise VO2 at 80% VT and velocity, as described by Capelli et al.9

Endurance performance (T400) was recorded as the time performed in an official 400 m freestyle competition within one month of the other tests.

All statistical analyses were performed using The Statistical Package for the Social Sciences (version 17.0, SPSS, Chicago, IL). Pearson’s product–moment correlation coefficient was used to establish correlations between physiological measures and T400. Paired Student’s t-tests were used to determine the significance of intra-individual differences in the measured and modelled parameters. Stepwise multiple regression was used to formulate an equation to identify the primary physiological determinant(s) of 400 m swimming performance. Statistical significance was set at $p < 0.05$.

3. Results

Absolute and relative VO2max, maximal heart rate (HRmax), maximal lactate (Lamax) determined at vVO2max (1.46 ± 0.07 m s⁻¹) were 4.18 ± 0.76 l min⁻¹, 55.6 ± 6.4 ml kg⁻¹ min⁻¹, 180 ± 7.1 b min⁻¹ and 10.4 ± 1.8 mmol l⁻¹, respectively. VO2 at VT was 41.9 ± 5.7 ml kg⁻¹ min⁻¹ and 86.4 ± 2.5% VO2max. Swimming economy was 0.75 ± 0.09 kJ m⁻¹. T400 was 251.4 ± 12.5 s.

The VO2 kinetics parameters of the square wave transitions are described in Table 1. The amplitude of the primary phase and the oxygen uptake at the end of each exercise bout were higher in S than in H exercise ($p = 0.00$).

The modelled response of a typical subject during H and S transitions from rest is provided in Fig. 1.

The amplitude ($A_p$, $A_{sc}$), time delay ($tdp$, $tdc$), time constant ($\tau_p$, $\tau_{sc}$), of the primary phase and slow component, respectively. $%A_{sc}$: relative contribution of slow component in relation to the end exercise VO2 of that bout, ISD: individual snorkel delay, End-exercise VO2: VO2 at the end of the constant load exercise corrected for body mass and relative to VO2max; End-exercise HR: heart rate at the end of the constant load exercise, End-exercise La: lactate concentration at the end of the swimming bout.

Table 1 shows the results of the stepwise regression analysis between the predictor variables and 400 m swimming performance.

The single best predictor of performance, out of the variables that were assessed in this study (i.e. absolute and relative $\dot{V}O_2_{max}$, HR$_{max}$, $L_a_{max}$, $v\dot{V}O_2_{max}$, VO$_2$ at VT, and the variables that are described in Table 1), was $\dot{V}O_2_{max}$. $\dot{V}O_2_{max}$ explained 80% of the variation in swimming performance between participants. However, when only ventilatory parameters and no speed related parameters were included in the regression model, the predictive accuracy of the latter for 400 m time was increased by the inclusion of absolute $\dot{V}O_2_{max}$ and $r_p(H)$.

4. Discussion

The main finding of this investigation was that the $\dot{V}O_2$ kinetics of the primary phase were associated with performance during high-intensity swimming. Specifically, $r_p$ during both heavy- and severe-intensity transitions was positively correlated with the time taken to complete a 400 m freestyle competition swim. This result agrees with those obtained for other exercise modes$^{7,8}$ and supports the notion that the primary phase of $\dot{V}O_2$ kinetics is an important determinant of athletic performance.

According to Gayda et al., it could be argued that the use of the Aquatrainer swimming snorkel underestimates the $\dot{V}O_2$ measurements due to the increased dead space$^{21}$ However, said study neither involved trained athletes nor accessed $\dot{V}O_2$ kinetics data. The fact that the authors did not correct their flowmeter temperature for ambient temperature, as requested by the manufacturers, may explain some of the discrepancies observed.$^{22}$ Furthermore, a previous study from our research group has found no differences between the $\dot{V}O_2$ kinetics parameters that are obtained when the Aquatrainer swimming snorkel and a conventional facemask are used,$^{17}$ confirming the validity of the measurements that are obtained with it.

The fact that the amplitude of the $\dot{V}O_2$ primary component, the end-exercise $\dot{V}O_2$, heart rate and lactate values that we observed were significantly higher in severe exercise than in heavy exercise, was not a surprising result as greater energy expenditure is expected at higher work intensities.$^{23}$

However, no significant difference between $r_pH$ and $r_pS$ was observed (15.8 vs. 15.8). Our $r_p$ values were also similar to those reported previously, by Hill et al.,$^{24}$ for running. $r_p$ for both heavy and severe exercise were correlated with T400 ($r = 0.62$ and $r = 0.61$, respectively). This is in accordance with the results of Kilding et al.,$^7$ for moderate intensity running. Furthermore, Ingham et al.$^9$ found that $r_p$ in heavy-intensity exercise both discriminates between elite- and club-level rowers, and is significantly correlated with the velocity obtained during a 2000 m rowing trial. The swimming event that we investigated is of similar duration. Faster $\dot{V}O_2$ kinetics reflects an increased oxidative contribution to energy transfer, which decreases the disruption caused by greater levels of anaerobiosis (such as reduced lactate accumulation, less type II fibre recruitment and less perturbation of cellular redox potential$^{25}$). Shorter time constants have been related to both increased time to exhaustion and fatigue tolerance,$^{4,5}$ and, consequently, might be expected to reflect better performance in swimming events of 3–5 min duration.

As has been previously reported,$^{26,27}$ our results confirm the existence of a $\dot{V}O_2$ slow component during swimming bouts that are performed above the first ventilatory threshold. However, contrary to our hypothesis, the amplitude of the slow component was not significantly correlated with middle distance swimming performance. This is unexpected because the slow component reflects greater metabolic inefficiency.$^{28}$

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Table 2

Stepwise regression for predicting 400 m freestyle performance.

<table>
<thead>
<tr>
<th>Regression model</th>
<th>$R$</th>
<th>$R^2$</th>
<th>Adj. $R^2$</th>
<th>SEE</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[-150.9 \dot{V}O_2_{max}(m \cdot s^{-1})] + 472.1$</td>
<td>0.89</td>
<td>0.80</td>
<td>0.78</td>
<td>5.87</td>
<td>0.00</td>
</tr>
<tr>
<td>$[-0.1 \dot{V}O_2_{max}(ml \cdot min^{-1}) + [1.44 \times r_pH(s)] + 272.4]$</td>
<td>0.92</td>
<td>0.84</td>
<td>0.81</td>
<td>5.66</td>
<td>0.00</td>
</tr>
</tbody>
</table>

$R$: coefficient of determination and SEE: standard error of the mean.
One possible explanation is that slow component amplitude is already minimised in highly trained individuals and, therefore, differences in performance between the individual athletes within our relatively homogeneous group of study participants were attributable to other factors. As such our results could be said to reflect those of Ingham et al.—who did not find differences between elite- and club-level rowers in the amplitude of the slow component. It may also be the case that the duration of the 400 m swim trial was not sufficiently long for the slow component to manifest itself as a determinant of performance.

Surprisingly, we observed a trend for the slow component to be lower in severe intensity exercise than in heavy swimming, perhaps due to the fact that, at the higher intensity, the increase in the VO\textsubscript{2} response is limited by the athletes’ VO\textsubscript{2}max.

When only the ventilator parameters were accounted, τ\textsubscript{pH} together with absolute VO\textsubscript{2}, could be considered valid predictors of 400-m swimming performance. VO\textsubscript{2} kinetics is a non-invasive measure of the swimmers, ability to cope with increased metabolic demand and the incorporation of the time constant in a regression model to predict performance provides further support for the critical role of VO\textsubscript{2} kinetics as a determinant of performance.

However, stepwise multiple regression analysis revealed that υVO\textsubscript{2}max was the best single predictor of, accounting for 80% of the variability in, middle-distance swimming performance. This is in line with the model for 5 km running performance that was proposed by Kilding et al., as well as with previous studies that assessed υVO\textsubscript{2}max and performance during swimming. For example, Klintou and Montepetit reported a significant correlation between 400 m performance and υVO\textsubscript{2}max.

It has been suggested that swimming performance depends on the interaction of multiple biomechanical, physical and physiological factors. The interaction of these factors, as well as their great inter-individual variability, might make the importance of physiological parameters appear less evident. Therefore, the supremacy of υVO\textsubscript{2}max as a single best predictor of middle-distance performance is not surprising. υVO\textsubscript{2}max is seen by some to both combine VO\textsubscript{2}max and exercise economy into a single factor, and to more fully explain individual differences in performance than either of the latter measures in isolation.

5. Conclusions

We have shown that faster kinetics during the primary phase of the VO\textsubscript{2} response in square-wave transitions from rest to heavy and severe swimming exercise, but not the slow component, is associated with better performance during middle-distance swimming.

However, υVO\textsubscript{2}max, which is a function of both exercise economy and maximal oxygen uptake, seems to be a better single predictor of T400.

Practical implications

This study provides the following information to coaches regarding physiological parameters that seem to be important for middle distance swimming performance:

- υVO\textsubscript{2}max is the single best predictor of middle distance swimming performance, accounting for 80% of the variation in T400.
- υVO\textsubscript{2}max and τ\textsubscript{pH} are also highly correlated with T400. Therefore, the velocity at which the swimmer can increase oxygen consumption a few seconds after the beginning of high intensity exercise seems to be important in middle distance swimming events.
- A single bout of 6-min of severe swimming exercise at a constant speed is sufficient to attain VO\textsubscript{2}max.
- Although it is not clearly established what type of training design (as regards changes in volume, intensity and duration) can be used to optimise improvements in VO\textsubscript{2} kinetics, a series of “all-out” cycle sprints has been shown to induce a shortening of τ\textsubscript{p} (by 25% and 21%, in the case of moderate and severe exercise, respectively), whilst moderate exercise has not. Therefore it seems logical that high intensity aerobic interval training or repeated sprints should be emphasized in the training of middle distance swimmers.

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