Exercise Modality Effect on Bioenergetical Performance at $\dot{V}O_{2max}$ Intensity

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ABSTRACT

SOUSA, A., P. FIGUEIREDO, P. ZAMPARO, D. B. PYNE, J. P. VILAS-BOAS, and R. J. FERNANDES. Exercise Modality Effect on Bioenergetical Performance at $\dot{V}O_{2max}$ Intensity. *Med. Sci. Sports Exerc.*, Vol. 47, No. 8, pp. 1705–1713, 2015. **Purpose**: A bioenergetical analysis of different exercise modes near maximal oxygen consumption ($\dot{V}O_{2max}$) intensity is scarce, hampering the prescription of training to enhance performance. We assessed the time sustained in swimming, rowing, running, and cycling at an intensity eliciting $\dot{V}O_{2max}$ and determined the specific oxygen uptake ($\dot{V}O_2$) kinetics and total energy expenditure ($E_{tot\text{-}tlim}$). **Methods**: Four subgroups of 10 swimmers, 10 rowers, 10 runners, and 10 cyclists performed (i) an incremental protocol to assess the velocity ($v\dot{V}O_{2max}$) or power ($w\dot{V}O_{2max}$) associated with $\dot{V}O_{2max}$ and (ii) a square wave transition exercise from rest to $v\dot{V}O_{2max}$/$w\dot{V}O_{2max}$ to assess the time to voluntary exhaustion (Tlim-100%$\dot{V}O_{2max}$). The $\dot{V}O_2$ was measured using a telemetric portable gas analyzer (K4b^2, Cosmed, Rome, Italy) and $\dot{V}O_2$ kinetics analyzed using a double exponential curve fit. $E_{tot\text{-}tlim}$ was computed as the sum of its three components: aerobic (Aer), anaerobic lactic (Ana_{lac}), and anaerobic alactic (Ana_{alac}) contributions. **Results**: No differences were evident in Tlim-100% $\dot{V}O_{2max}$ between exercise modes (mean ± SD: swimming, 187 ± 25; rowing, 199 ± 52; running, 245 ± 46; and cycling, 227 ± 48 s). In contrast, the $\dot{V}O_2$ kinetics profile exhibited a slower response in swimming (21 ± 3 s) compared with the other three modes of exercise (rowing, 12 ± 3; running, 10 ± 3; and cycling, 16 ± 4 s) ($P < 0.001$). $E_{tot\text{-}tlim}$ was similar between exercise modes even if the Ana_{lac} contribution was smaller in swimming compared with the other sports ($P < 0.001$). **Conclusion**: Although there were different $\dot{V}O_2$ kinetics and ventilatory patterns, the Tlim-100%$\dot{V}O_{2max}$ was similar between exercise modes most likely related to the common central and peripheral level of fitness in our athletes. **Key Words:** EXERCISE MODES, TIME LIMIT, OXYGEN UPTAKE KINETICS, ENERGY EXPENDITURE

The bioenergetics of cyclic sports has been studied since the 1920s, with a focus on locomotion and its contribution to athletic performance (50). The level of maximal oxygen uptake ($\dot{V}O_{2max}$) as a marker of exercise intensity is considered one of the primary areas of interest in training and performance diagnosis, but the capacity to sustain it as a function of time has received little attention in cyclic sports (26). This capacity, usually expressed as a time limit (in this case, Tlim-100%$\dot{V}O_{2max}$), quantifies the ability to maintain that specific constant velocity (or power output) (4). Most of the studies conducted reported similar values of Tlim-100%$\dot{V}O_{2max}$ between several exercise modes, such as cycling, kayaking, swimming, and running (5), although kayakers performed longer than cyclists (24). However, no studies have analyzed other physiological variables in parallel, and factors involved in determining Tlim-100%$\dot{V}O_{2max}$ across a range of sports remain unclear.

It is widely appreciated that sustaining exercise beyond a few seconds depends on the appropriate supply and use of oxygen (31). Thus, differences in Tlim-100%$\dot{V}O_{2max}$ between exercise modes could be explained by specific oxygen uptake ($\dot{V}O_2$) responses to exercise. Most of the studies have compared only the physiological responses of different exercise modes, and very few have also addressed the kinetic parameters of the underlying (transient) $\dot{V}O_2$ kinetic response. Studies have almost exclusively compared running with cycling (15,28,32), suggesting that the time constant and $\dot{V}O_2$ slow component in running is shorter compared with cycling. However, no studies have compared directly the $\dot{V}O_2$ kinetics within other exercise modes.

Different performances in Tlim-100%$\dot{V}O_{2max}$ can also be derived from distinct energetic inputs at this intensity. At submaximal (moderate) exercise intensity, $\dot{V}O_2$ is sufficient to provide the total energy expenditure (E_{tot}) after steady

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state is achieved. However, at higher exercise intensities, not accounting for the anaerobic contribution, results in an underestimation of E_{tot}, with a negative effect on understanding the performance at this intensity. In fact, at short competitive distances where $\dot{V}O_2$ steady-state cannot be attained, the determination of E_{tot} is scarce, with some research in swimming (11), running (21), cycling (12), and rowing (13), but no studies have compared E_{tot} directly between different exercise modes.

The mechanical differences between running and cycling have been attributed to the muscular contraction regimen (40). Although both activities are performed by muscle contraction of the lower limbs, the concentric work of cycling has lower locomotion efficiency than running, which relies on a stretch-shortening cycle (7). On the other hand, the recruitment of a greater muscle mass could potentially compromise muscle perfusion (46). Rowing engages most of the major muscle groups of the upper and lower body, such that performance, especially during heavy exercise, could be compromised compared with other exercise modes where a lower fraction of the total muscle mass is recruited (47). Of all the exercise modes, swimming requires larger energy expenditure, and thus, a lower overall efficiency of progression occurs (20). In addition, the horizontal position adopted by swimmers, with lower muscle perfusion pressure, may be a key difference between swimming and the other exercise modes (34).

Whether these different mechanical factors between exercise modes influence the overall bioenergetic responses is unknown. This analysis is needed to understand the physiological mechanisms that underpin performance at an intensity eliciting $\dot{V}O_{2max}$. The purpose of this study was to compare the Tlim-100%$\dot{V}O_{2max}$, $\dot{V}O_2$ kinetics response, and E_{tot} in swimmers, rowers, runners, and cyclists. We hypothesized that the performance at Tlim-100%$\dot{V}O_{2max}$ would not differ among the exercise modes, but their different mechanical demands might elicit different $\dot{V}O_2$ kinetics and energy expenditure patterns. This analysis will provide new insights in the selection of the intensity/duration of training sets near the $\dot{V}O_{2max}$ intensity.

METHODS

Subjects. Forty male subjects, highly trained (≥6 times per week) and regularly involved in competitive sports, participated in this study. The sample consisted of four groups of 10 × 400-m swimmers; 10 × 2000-m rowers; 10 × 1500–3000-m runners, and 10 × middle-distance road cyclists. Their physical characteristics are presented in Table 1. All subjects signed an informed consent form, avoided strenuous exercise in the 24 h before each testing session, and were well hydrated and abstained from food, caffeine, and alcohol in the 3 h before testing. The Institutional Review Board of the University of Porto, Faculty of Sport, approved the study design.

Experimental design. The subjects were tested on two occasions. In the first session, $\dot{V}O_{2max}$ and the velocity (v$\dot{V}O_{2max}$) or the power (w$\dot{V}O_{2max}$) associated with $\dot{V}O_{2max}$ intensity were determined with a progressive incremental protocol until exhaustion. In the second session, all subjects completed a square wave transition exercise from rest to v$\dot{V}O_{2max}$ or w$\dot{V}O_{2max}$ until exhaustion to assess the Tlim-100%$\dot{V}O_{2max}$. Verbal encouragement was given to motivate the subjects to perform their best effort in the incremental protocols and for as long as possible during the square wave exercises.

Incremental protocols and square wave exercises. The incremental protocols varied according to the specificity of each sport: (i) swimmers performed an intermittent protocol using the front crawl technique in a 25-m swimming pool, with initial velocity set at the individuals' performance on the 400-m freestyle followed by seven increments of velocity (25). In between 200-m steps, velocity was incremented by 0.05 $m \cdot s^{-1}$ with a 30-s interval until exhaustion, controlled by a visual pacer with flashing lights at the bottom of the swimming pool (TAR.1.1, GBK-electronics, Aveiro, Portugal); (ii) runners performed an intermittent protocol on a 400-m outdoor track field, with the initial velocity set according to the individuals' performance on previous similar tests. The velocity was then increased by 1 $km \cdot h^{-1}$ for each 800-m step with a 30-s interval until exhaustion, controlled by audio feedback emitted in markers placed at 100-m intervals; (iii) cyclists performed a continuous protocol with 2-min step duration, increments of 40 W between steps, and a self-selected cadence between 70 and 90 rpm on a Power Tap trainer (CycleOps, Madison, WI, USA). The initial power was set according to the subject's fitness level and performance in previous tests; and (iv) rowers performed an intermittent protocol of 2-min step duration, increments of 40 W, and a 30-s interval between each step and a self-selected cadence ranging between 30 and 40 rpm on a rowing ergometer (Concept II, Model D, CTS, Inc). Similar to cyclists, the initial power was set according to the subject's fitness level and previous testing performance. During the cycling and rowing protocols, the predefined power was controlled by visual feedback.

TABLE 1. Physical characteristics for highly trained male swimmers, rowers, runners, and cyclists (mean ± SD).

Group	Swimmers	Rowers	Runners	Cyclists
Age, yr	17.0 ± 0.9*	26.4 ± 5.2	28.7 ± 4.4	23.3 ± 1.9
Height, m	1.80 ± 0.06	1.80 ± 0.06	1.75 ± 0.06	1.78 ± 0.06
Body mass, kg	70.3 ± 6.2	75.6 ± 4.0	61.9 ± 6.4*	70.1 ± 4.3

*Significant differences between groups are shown by $P \leq 0.05$.

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Approximately 24 to 48 h after, all subjects performed a square wave transition exercise from rest to their previously determined $v\dot{V}O_{2max}$ or $w\dot{V}O_{2max}$ until exhaustion to assess Tlim-100%$\dot{V}O_{2max}$, using the same feedback stimulus as in the incremental protocol. In all exercise modes, this test consisted of three distinct phases: (i) 10-min warm-up exercise at 50% of the $v\dot{V}O_{2max}/w\dot{V}O_{2max}$; (ii) 5-min recovery, and (iii) the maintenance of the previously determined $v\dot{V}O_{2max}/w\dot{V}O_{2max}$ until exhaustion. The square wave transition exercise ended when the subject could no longer follow for three consecutive occasions the velocity/power feedback stimulus.

Experimental measurements. Respiratory and pulmonary gas-exchange variables were measured using a telemetric portable gas analyzer ($K4b^2$, Cosmed, Rome, Italy). In swimming, this apparatus was suspended over the water (at a 2-m height) in a steel cable following the swimmer along the pool to minimize disturbance of the normal swimming movements. This equipment was connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system (1). In-water starts and open turns, without underwater gliding, were used. In the rowing, running, and cycling exercises, the subjects breathed through a traditional facemask ($K4b^2$, Cosmed, Rome, Italy). The measurement device was placed near the center of mass of the body, adding only 800 g to the total mass of the subject. The gas analyzers in the system were calibrated before each test with gases of known concentration (16% O_2 and 5% CO_2) and the turbine volume transducer calibrated with a 3-L syringe. Heart rate (HR) was monitored continuously by a Polar Vantage NV (Polar electro Oy, Kempele, Finland) that telemetrically emitted the data to the $K4b^2$ portable unit. Capillary blood samples (5 μL) for lactate concentrations ($[La^-]$) were collected from the earlobe before the exercise, during the 30-s intervals (in the incremental protocols) and immediately at the end of exercise during the first, third, fifth, and seventh minute of the recovery period (in both protocols) until maximal values ($[La^-]_{max}$) were reached (Lactate Pro, Arkay, Inc, Kyoto, Japan).

Data analysis. Errant breaths (e.g., caused by swallowing, coughing, and signal interruptions) were omitted from the $\dot{V}O_2$ analysis by including only those that were between $\dot{V}O_2$ mean ± 4 SDs. After this process, individual breath-by-breath $\dot{V}O_2$ responses were smoothed using a 3-breath moving average and time average every 5 s. $\dot{V}O_{2max}$ was defined as a plateau in $\dot{V}O_2$ despite an increase in velocity/power, $[La^-] \geq 8$ mmol·L^{-1}, respiratory exchange ratio $R \geq 1.0$, HR >90% of [220 – age], and a volitional exhaustion (controlled visually and case-by-case) (29).

Velocity $\dot{V}O_{2max}$ and $w\dot{V}O_{2max}$ were estimated as the velocity or power corresponding to the first stage of the test that elicited $\dot{V}O_{2max}$. If a plateau of less than 2.1 mL·min^{-1}·kg^{-1} could not be observed, the $v\dot{V}O_{2max}$ and the $w\dot{V}O_{2max}$ were calculated as previously described (37). Physiological measures of $\dot{V}O_{2max}$, maximal HR (HR_{max}), respiratory quotient (R), and minute ventilation ($\dot{V}_E$) were measured over the last 60 s of the exercise in the incremental protocol and square wave transition exercise.

The total energy expenditure for each exercise step during the incremental protocols ($E_{tot\text{-}inc}$) was determined via the addition of the net $\dot{V}O_2$ and O_2 equivalents of the net $[La^-]$ values, using the proportionality constant of 2.7 mL·kg^{-1}·mM^{-1} for swimming (11) and 3 mL·kg^{-1}·mM^{-1} for rowing, running, and cycling (12). The estimated total energy expenditure during the square wave transition exercises ($E_{tot\text{-}tlim}$) was assumed to be the sum of the aerobic (Aer), anaerobic lactic (Ana_{lac}), and anaerobic alactic (Ana_{alac}) energies (50).

The Aer was calculated from the time integral of the net $\dot{V}O_2$. This energy contribution (mL O_2) was then expressed in kilojoule assuming an energy equivalent of 20.9 kJ·L^{-1} (50). The Ana_{lac} was assessed through the energy derived from lactic acid production (equation 1):

$$Ana_{lac} = b[La^-]_{bnet}M \quad [1]$$

where $[La^-]_{bnet}$ is the net accumulation of lactate after exercise, b is the energy equivalent for $[La^-]$ accumulation in blood (as previously described), and M (kg) is the mass of the subject. This energy contribution (mL O_2) was then expressed in kilojoule assuming an energy equivalent of 20.9 kJ·L $^{-1}$ (50). The Ana_{alac} was assessed from the maximal PCr splitting in the contracting muscle (equation 2):

$$Ana_{alac} = PCr \times (1 - e^{-t/\tau})M \quad [2]$$

where Ana_{alac} is the anaerobic alactic contribution, t (s) is the exercise time, τ is time constant of the PCr splitting at the onset of exhausting exercise—23.4 s (8), M (kg) is the body mass, and PCr is the phosphocreatine concentration at rest. This latter value was estimated assuming that in transition from rest to exhaustion, its concentration decreases by 18.55 mM^{-1}·kg^{-1} muscle wet weight (in a maximally working muscle mass equal to 30% of the overall body mass). Ana_{alac} was thus expressed in kilojoule by assuming an energy equivalent of 0.468 kJ·mM^{-1} and a P/O_2 ratio of 6.25 (50).

For the $\dot{V}O_2$ kinetic analysis, the first 20 s of data after the onset of exercise (cardiodynamic phase) was not considered for model analysis. To allow the comparison of the $\dot{V}O_2$ response, data were modeled using a double exponential approach to isolate the $\dot{V}O_2$ fast component response. A nonlinear least squares method was implemented in MatLab Software (Mathworks, USA) to fit the $\dot{V}O_2$ data with each model (equation 3):

$$\dot{V}O_2(\tau) = A_0 + A_1\left(1 - e^{-(\tau - TD_1/\tau_1)}\right) + A_2\left(1 - e^{-(\tau - TD_2/\tau_2)}\right) \quad [3]$$

where $\dot{V}O_2$ (τ) represents the relative $\dot{V}O_2$ at the time τ, A_0 is the $\dot{V}O_2$ at rest (mL·kg^{-1}·min^{-1}), and A_1 and A_2 (mL·kg^{-1}·min^{-1}), TD_1 and TD_2 (s), and τ_1 and τ_2 (s) are the amplitudes, corresponding time delays, and time constants of the fast and slow $\dot{V}O_2$ components, respectively.

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TABLE 2. $\dot{V}O_{2max}$ (absolute and relative), HR_{max}, R, $\dot{V}_E$, and $[La^-]_{max}$ obtained at the end of the incremental protocols and square wave transition exercises for swimmers, rowers, runners, and cyclists (mean ± SD).

		Swimmers	Rowers	Runners	Cyclists
$\dot{V}O_{2max}$, L·min^{-1}	Inc	4.24 ± 0.60^{Ro}	5.02 ± 0.28	4.33 ± 0.45^{Ro}	4.48 ± 0.59
	Tlim	4.26 ± 0.61	4.89 ± 0.26	4.52 ± 0.68	4.35 ± 0.71
$\dot{V}O_{2max}$, mL·kg^{-1}·min^{-1}	Inc	61.11 ± 5.24^{Ru}	66.84 ± 3.88	71.38 ± 4.15	64.53 ± 5.00^{Ru}
	Tlim	60.92 ± 5.46^{Ru}	64.95 ± 4.18^{Ru}	73.08 ± 5.14^{Cy}	63.04 ± 8.35
HR_{max}, bpm	Inc	183 ± 8	188 ± 10	185 ± 8	182 ± 10
	Tlim	181 ± 5	187 ± 10	184 ± 7	178 ± 6
R	Inc	$0.94 \pm 0.07^{Ro,\ Ru,\ Cy}$	1.05 ± 0.03^{Cy}	1.06 ± 0.06^{Cy}	1.18 ± 0.06
	Tlim	$0.99 \pm 0.09^{Ro,\ Cy}$	1.09 ± 0.04^{Cy}	1.07 ± 0.07	1.20 ± 0.07^{Ru}
$\dot{V}_E$, L·min^{-1}	Inc	$111.85 \pm 23.10^{Ro,\ Ru,\ Cy}$	177.58 ± 18.17	156.79 ± 18.23	166.12 ± 16.12*
	Tlim	$117.47 \pm 18.38^{Ro,\ Ru,\ Cy}$	172.24 ± 18.76^{Ru}	149.44 ± 17.14	153.23 ± 13.98
$[La^-]_{max}$, mmol·L^{-1}	Inc	8.37 ± 1.07^{Cy}	10.64 ± 2.44	9.77 ± 2.09	11.33 ± 1.68
	Tlim	$8.66 \pm 0.69^{Ro,\ Ru,\ Cy}$	11.03 ± 1.01	11.58 ± 2.02	11.19 ± 2.79

Significant differences between both tests are shown by asterisk, and significant differences between the groups are shown by superscripted Ro (rowers), Ru (runners), and Cy (cyclists) ($P \leq 0.05$).
HR_{max}, maximal heart rate; R, respiratory quotient; $\dot{V}_E$: minute ventilation.
$\dot{V}O_{2max}$, absolute and relative maximal oxygen consumption; $[La^-]_{max}$, maximal blood lactic acid concentrations; Inc, incremental protocols; Tlim, square wave transition exercises.

Statistical analysis. Individual mean and SD computations for descriptive analysis were obtained and reported for all variables. Measures of skewness, kurtosis, and the Shapiro–Wilk test were used to assess the normality and homogeneity of the data. The differences between pulmonary, metabolic, performance, and kinetic variables in-between exercise modes were tested using a one-way ANOVA. To test the differences between the incremental protocol and the square wave transition exercises in each exercise mode, a paired *t*-test was conducted. Simple linear regression and Pearson correlation and partial correlation coefficients were also used to characterize the degree of association between the studied variables. All statistical procedures were conducted with SPSS 10.05, and the significance level was set at 5%. Magnitudes of standardized effects [*f*] were determined against the following criteria: small, 0.2–0.5; moderate, 0.5–0.8, and large, >0.8.

RESULTS

Pulmonary and metabolic parameters assessed during the incremental protocols and the square wave transition exercises are reported in Table 2 for each exercise mode. With the exception of cyclists who exhibited higher values of $\dot{V}_E$ in the incremental protocol compared to the square wave transition exercise, no substantial differences were observed between the final values in both tests.

Apart from HR_{max}, a comparison between exercise modes showed that swimmers often presented lower ventilatory and metabolic mean values (and a small to moderate standardized effect, *f*) in the (i) incremental protocol—absolute $\dot{V}O_{2max}$ ($P < 0.001$; $f = 0.28$), relative $\dot{V}O_{2max}$ ($P < 0.001$; $f = 0.42$), R ($P < 0.001$; $f = 0.67$), $\dot{V}_E$ ($P < 0.001$; $f = 0.65$), $[La^-]_{max}$ ($P < 0.05$; $f = 0.27$), and the (ii) square wave transition exercise—relative $\dot{V}O_{2max}$ ($P < 0.001$; $f = 0.39$), R ($P < 0.001$; $f = 0.55$), $\dot{V}_E$ ($P < 0.001$; $f = 0.59$), and $[La^-]_{max}$ ($P < 0.05$; $f = 0.29$) than other sports. The relationship between $E_{tot\text{-}inc}$ and the correspondent steps of the incremental protocol for all exercise modes is shown in Figure 1.

The mean value of $E_{tot\text{-}inc}$ ranged between 40 and 55 mL·kg^{-1}·min^{-1} for the swimmers, 40 and 65 mL·kg^{-1}·min^{-1} for the rowers, 50 and 70 mL·kg^{-1}·min^{-1} for the runners, and 30 and 70 mL·kg^{-1}·min^{-1} for the cyclists. Significant differences in the slopes of the relationship between $E_{tot\text{-}inc}$ and the corresponding steps of the incremental protocol were evident between all groups (Fig. 1). The cyclists had the steepest slope of variation in $E_{tot\text{-}inc}$ as a function of power output in the incremental protocol, and swimmers, by having a slope less than 50% than cyclists, exhibited the shallowest variation.

The $v\dot{V}O_{2max}$ was 76% slower in swimming compared to running (1.41 and 5.45 m·s^{-1}, respectively), whereas $w\dot{V}O_{2max}$ was very similar between rowing and cycling (402 and 392 W, respectively). The times sustained at 100%$\dot{V}O_{2max}$ and energy contributions (absolute, kJ; and relative, %) obtained during the square wave transition exercises for all exercise modes are shown in Figure 2.

Although $E_{tot\text{-}tlim}$ mean values were similar between the exercise modes, both the absolute (kJ) Ana_{lac} ($P < 0.001$; $f = 0.43$) contributions in swimming and the Ana_{alac} ($P < 0.001$; $f = 0.49$) contributions in running were lower compared with the other exercise modes. Moreover, the relative (%) Ana_{alac} contribution was higher in swimming compared with the other exercise modes ($P < 0.05$; $f = 0.18$); no substantial differences were

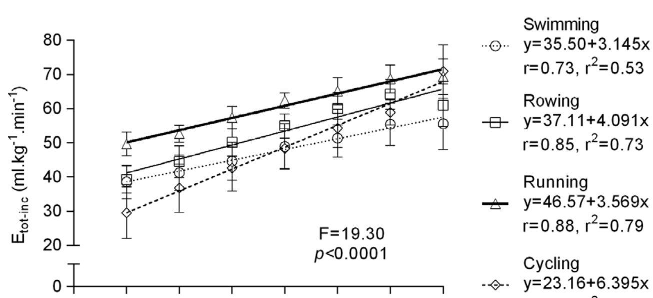

FIGURE 1—Relationship between $E_{tot\text{-}inc}$ and the correspondent incremental protocol steps for $\dot{V}O_{2max}$ and $v\dot{V}O_{2max}/W\dot{V}O_{2max}$ assessment in all exercise modes. The regression equations, correlation and determination coefficients, and the *F* test results are presented.

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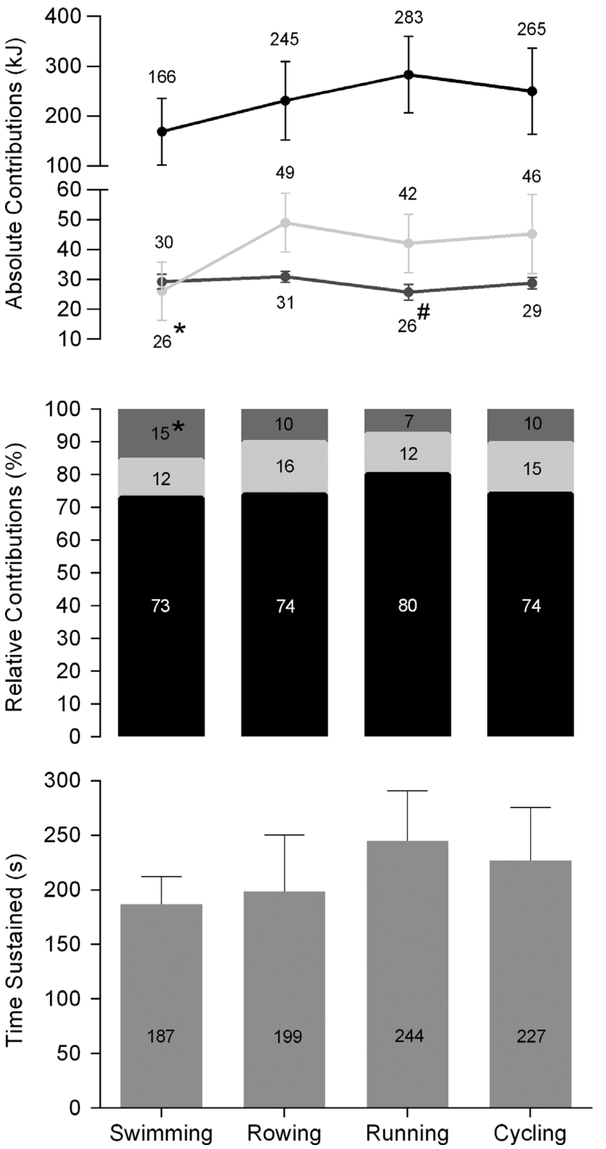

FIGURE 2—Upper panel, Mean and SD aerobic (*black*), anaerobic lactic (*light gray*), and anaerobic alactic (*dark gray*) absolute contribution values (rounded to the closest unit, kJ) obtained during the square wave transition exercises for all exercise modes. Significant differences between swimming and the other groups are shown by *asterisk* (anaerobic lactic contributions), and significant differences between running and the other groups are shown by the *number sign* (#, anaerobic alactic contributions). Middle panel, Mean aerobic (*black*), anaerobic lactic (*light gray*), and anaerobic alactic (*dark gray*) relative contribution values (rounded to the closest unit, %) obtained during the square wave transition exercises for all exercise modes. Significant differences between swimming and the other groups shown by *asterisk* (anaerobic alactic contributions). Lower panel, Mean and SD values of time sustained at 100%$\dot{V}O_{2max}$ values (rounded to the closest unit) obtained during the square wave transition exercises for all exercise modes.

observed regarding the time sustained at 100% of $\dot{V}O_{2max}$ in-between groups.

The $\dot{V}O_2$ kinetic parameters obtained during the square wave transition exercises for swimmers, rowers, runners and cyclists are shown in Table 3. The A_0 was higher in swimming compared to running and cycling and lower in running compared to rowing and cycling ($P < 0.05$; $f = 0.29$). In contrast, A_1 was lower in swimming compared to the other modes of exercise and lower in rowing and cycling compared to running ($P < 0.001$; $f = 0.64$). Swimmers exhibited slower $\dot{V}O_2$ kinetics compared to the other exercise modes, and cyclists exhibited a faster $\dot{V}O_2$ kinetics compared to runners ($P < 0.001$; $f = 0.67$). The A_2 values (absolute and relative) were not substantially different between exercise modes.

Correlations between Tlim-100%$\dot{V}O_{2max}$ and $\dot{V}O_{2max}$ and $E_{tot\text{-}tlim}$ and $\dot{V}O_{2max}$ in the square wave transition exercises are shown in Figure 3 for all groups combined. A moderate relationship was observed between the $\dot{V}O_{2max}$ reached during the square wave transition exercises and time sustained and between $\dot{V}O_{2max}$ and $E_{tot\text{-}tlim}$. No significant relationships were evident between the $\dot{V}O_{2max}$ reached during the incremental protocols and the time sustained in the square wave transition exercises when considering all subjects and within each exercise mode. Regarding the $\dot{V}O_2$ kinetic parameters, and considering all subjects, moderate to large relationships were observed (τ_1 with A_1: $r = -0.60$; $P < 0.001$; τ_1 with A_2: $r = 0.42$; $P < 0.001$), which lost their significance when the time sustained variable was controlled for partial correlation.

DISCUSSION

The purpose of this study was to compare Tlim-100%$\dot{V}O_{2max}$ in swimmers, rowers, runners, and cyclists and to determine their $\dot{V}O_2$ kinetics response and maximal metabolic expenditure. The performance of the subjects at 100%$\dot{V}O_{2max}$ intensity regarding the time sustained was similar to corroborating the hypothesis that the Tlim-100%$\dot{V}O_{2max}$ would not differ among the exercise modes. Moreover, the hypothesis that their different mechanical factors would contribute to different $\dot{V}O_2$ kinetics and metabolic patterns was also confirmed, with substantial differences observed in $\dot{V}O_2$ kinetics (A_1 and τ_1) and metabolic profiles (Ana_{alac}) between exercise modes at 100%$\dot{V}O_{2max}$ intensity.

$\dot{V}O_{2max}$ is one of the most commonly measured parameters in the applied physiological sciences, and a variety of incremental exercise protocols are used. However, no significant differences were reported between laboratory and field conditions (2) and between 1- and 4-min step durations (36). The primary criteria for evaluating the quality of an incremental test is the occurrence of a $\dot{V}O_{2max}$ plateau (23), which usually occurs only for 50% of subjects (22), a value close to that observed in the current study (~40%). Therefore, the achievement of secondary objective criteria (*R*, HR_{max}, and $[La^-]$) increased the likelihood that the highest $\dot{V}O_2$ value achieved was the $\dot{V}O_{2max}$.

The mean $\dot{V}O_{2max}$ values observed at the end of the incremental protocols are in accordance with data reported previously for competitive-level swimmers (5,24), rowers (49), runners (6,44), and cyclists (16). The $\dot{V}O_{2max}$ values were higher in running compared with cycling and swimming, with no other substantial differences between the other exercise modes, probably owing to the use of larger muscle mass (27).

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TABLE 3. Values for the $\dot{V}O_2$ kinetic parameters in the square wave transition exercises for swimmers, rowers, runners, and cyclists (mean ± SD).

Kinetic Parameters	Swimmers	Rowers	Runners	Cyclists
A_0, mL·kg^{-1}·min^{-1}	23.6 ± 3.1^{Ru,Cy}	20.6 ± 3.6	18.5 ± 4.4^{Ro,Cy}	18.4 ± 2.1
A_1, mL·kg^{-1}·min^{-1}	33.2 ± 4.0^{Ro,Ru,Cy}	40.5 ± 4.8	48.3 ± 3.4^{Ro,Cy}	38.7 ± 4.6
A_1 95% confidence limits	(30.4–36.2)	(37.1–43.9)	(45.8–50.7)	(35.4–42.0)
TD_1, s	9.6 ± 2.8	6.9 ± 3.4	9.3 ± 4.1	12.4 ± 4.6
τ_1, s	20.7 ± 2.9^{Ro,Ru,Cy}	11.9 ± 2.6	9.6 ± 2.7^{Cy}	15.5 ± 3.9
τ_1 95% confidence limits	(18.6–22.8)	(9.9–13.8)	(7.6–11.6)	(12.7–18.2)
A_2, mL·kg^{-1}·min^{-1}	7.2 ± 3.1	5.3 ± 2.3	6.0 ± 2.0	6.9 ± 1.9
$\%A_2$, %	16.3 ± 9.7	11.5 ± 4.9	11.1 ± 3.8	15.1 ± 4.0
TD_2, s	71.8 ± 26.2	67.9 ± 9.8	88.8 ± 24.6	94.3 ± 28.2
τ_2, s	125.8 ± 27.9^{Ro,Ru,Cy}	57.9 ± 40.7	60.5 ± 43.4	65.9 ± 45.5

Significant differences between the groups are shown by superscripted Ro (rowers), Ru (runners), and Cy (cyclists) ($P \leq 0.05$).
A_0, $\dot{V}O_2$ at rest.
A_1 and A_2, amplitudes of the fast and slow components, respectively; TD_1 and TD_2, time delays of the fast and slow components, respectively; τ_1 and τ_2, time constants of the fast and slow components, respectively; $\%A_2$, relative contribution of slow component to net increase in $\dot{V}O_2$.

In addition, during running, the movement of the arms and trunk demands a significant O_2 requirement compared with cycling, where they have a lower contribution to the total exercise $\dot{V}O_2$ (28). In the current study, lower values of $[La^-]_{max}$ and $\dot{V}_E$ were reported in swimming compared with the other exercise modes (which can also explain the differences reported in the *R* mean values). Collectively, these data indicate that a lower metabolic acidosis occurs in swimming or that swimmers are less sensitive to it (5). As expected, pulmonary and metabolic values obtained at the end of the incremental protocols were similar to those obtained at the end of the square wave transition exercises, with the exception of $\dot{V}_E$ for cyclists. This lack of differences between both protocols is reported in literature for most sports, evidence of similar intensity in both tests (5,25).

The relationship between $E_{tot\text{-}inc}$ and the corresponding steps of the incremental protocol indicated that cyclists had a greater rise per step, followed by rowers, runners, and swimmers. The mean value of $E_{tot\text{-}inc}$ ranged between 30 and 70 mL·kg^{-1}·min^{-1} in cyclists and for each increment of 40 W in power, the metabolic expenditure increased by ~6 mL·kg^{-1}·min^{-1}, which was higher than rowing and running (~4 mL·kg^{-1}·min^{-1}) and swimming (~3 mL·kg^{-1}·min^{-1}). Thus, one notable difference between these exercise modes is the cost of exercise, suggesting that this measure depends not only on the aerobic and anaerobic contributions but also on the interval range of these contributions during incremental intensities. Although the pedaling frequency in cycling was controlled along the incremental protocol (70–90 rpm), it could have influenced the performance since the "energetically optimal cadence" (50–75 rpm) could not match the "freely chosen cadence" (80–100 rpm) (40). In this sense, during cycling exercise, and contrarily to rowing and running where the cadence has been described as having a lower effect on the exercise economy, the pedaling frequency should be strictly controlled.

In the current study, $w\dot{V}O_{2max}$ was not substantially different between rowing and cycling, suggesting that the higher active muscular mass attributed to rowing exercise (compared with cycling) did not influence the performance at 100% of $\dot{V}O_{2max}$, as previously shown (47). Since water is denser than the air, swimming requires a large energy expenditure to overcome the drag forces and has a lower overall efficiency of progression compared with running (20). Collectively, these factors lead to a large energy cost of transport, explaining the significant lower $v\dot{V}O_{2max}$ in swimming compared with running. Both $w\dot{V}O_{2max}$ and $v\dot{V}O_{2max}$ observed in the current study are in agreement with previous studies conducted in swimming (25), rowing (49), running (44), and cycling (3,16).

The lack of a substantial difference in Tlim-100%$\dot{V}O_{2max}$ between the exercise modes is consistent with previous reports for other forms of locomotion (5,24). Collectively, these studies demonstrate that the Tlim-100%$\dot{V}O_{2max}$ is independent of the exercise mode performed, as previously suggested for the critical power/velocity intensity (14). Although no substantial differences were observed in Tlim-100%$\dot{V}O_{2max}$ between the exercise modes, we recommend total exercise duration of ~200 s (for swimming and rowing) and ~250 s (for running and cycling) whenever $\dot{V}O_{2max}$ training intensity is to be enhanced. However, the mean time sustained values in the present study are lower than reported previously for swimming (25,26), running (6,9), and cycling (5,24). These differences are most likely explained by the innate ability and training status of the subjects among these studies. We are unaware of similar data for rowing exercise.

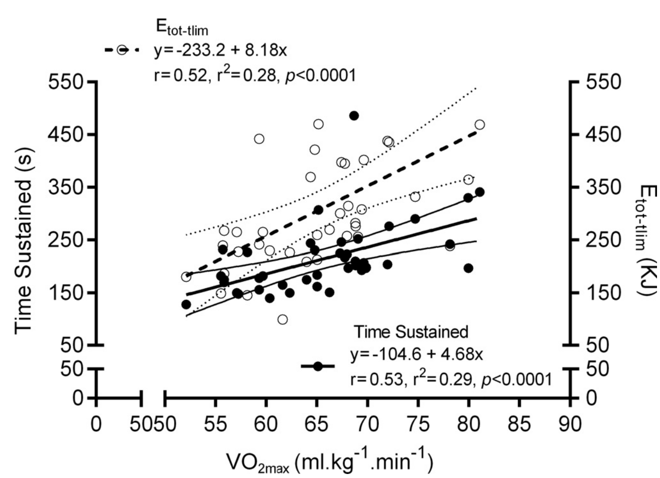

FIGURE 3—Relationships between $\dot{V}O_{2max}$ and time sustained (*filled circles*) and between $\dot{V}O_{2max}$ and $E_{tot\text{-}tlim}$ (*unfilled circles*) during the square wave transition exercises considering all subjects. The regression equations, determination and regression coefficients (±95% confidence limits), and significance level values are identified.

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In relation to $E_{tot\text{-}tlim}$, the absolute Aer contribution (kJ) was similar between the exercise modes; however, the Ana_{lac} and Ana_{alac} contributions (kJ) were found to be lower in swimming and running (respectively) compared with the other exercise modes. It should be pointed out that whereas the lower Ana_{lac} contribution (kJ) in swimming has to be attributed to the lower net accumulation of lactate after exercise (see equation 1), the lower Ana_{alac} contribution (kJ) in running can be simply attributed to the lower runners' body mass, since no differences were found in Tlim-100%$\dot{V}O_{2max}$ (the exercise time, *t*) and since the same percent of the overall body mass was assumed to correspond to the maximally working muscle mass (30%) in all exercise modes (see equation 2). Despite the existence of some caveats regarding the Ana_{alac} assessment method used, it is important to attempt to estimate this energy pathway in maximal (or near maximal) efforts, as proven previously for swimming exercise (48). With the exception of Ana_{alac} (%), which was higher in swimming compared with the other exercise modes, no substantial differences were observed in relative (%) contributions. In contrast to Tlim-100%$\dot{V}O_{2max}$, it seems that the specific mechanical factors (e.g., muscle contraction regimen and the ensuing muscle fiber recruitment profile itself) might have had an impact on the exercise energy contribution, which in turn, depends essentially on the type of exercise performed. In fact, it is well reported that the proportion of type I muscle fibers is substantially lower in the muscles of the upper body compared to those of the lower body (30). Knowing that arm stroke generates the most propulsive force in swimming (19), the higher Ana_{alac} found in swimming suggests a greater recruitment of type II muscle fibers, as reported during arm-crank exercise compared with cycling (35).

Although $\dot{V}O_2$ kinetics is well described in the literature, especially in running and cycling exercises, some kinetics parameters are influenced by the training level of the subjects (15,32). Therefore, the level of physical activity and performance of the subjects are likely to explain some inconsistencies between the current data and the literature, namely, in estimates of swimming A_2 (18,43), running τ_1 (39), and cycling A_1 and A_2 (10,42). A_1 mean values were lower in swimming compared with the other exercise modes. No comparisons are reported in literature between swimming and other forms of locomotion; however, these differences could be explained by the higher A_0 values observed in swimming. In fact, the normal constraints in the beginning of the exercise (entering the pool with the gas measurement apparatus) may confound the achievement of a baseline as low as those typically reported for laboratory testing. In addition, immersion in water induces a translocation of blood to the upper part of the body and a slower auto transfusion of fluid from cells to the vascular compartment, increasing stroke volume and cardiac output (41). These factors may also have contributed to higher A_0 values. The higher A_1 values in running compared with the other exercise modes can be explained by the higher $\dot{V}O_{2max}$ (15,28). In the present study, the absence of difference in A_1 values between rowing and cycling is also in agreement with previous reports (45).

The τ_1 was longer in swimming compared with other sports, although the swimmers were younger. Since τ_1 reflects the rate at which the $\dot{V}O_2$ response achieves the steady state, swimmers had a slower response toward the steady-state $\dot{V}O_2$. A key postural difference between swimming and the other exercise modes is that swimmers are in a horizontal position. It is known that in the supine position, muscle perfusion pressure is lower, resulting in a longer τ_1 (34). The supine position also induces an increased venous blood return but reduces blood hydrostatic pressure in the legs (38). Moreover, the inability to produce maximal muscle contractions (due to environment constraints) could limit a faster increase in $\dot{V}O_2$ kinetics. This finding suggests that swimmers, compared with athletes in the other exercise modes, would benefit more from a longer duration (~90 s) of exercise or training intervals whenever $\dot{V}O_{2max}$ training intensity is to be enhanced. In the current study, runners had a faster $\dot{V}O_2$ kinetics compared with cyclists, a fact already reported during an exercise intensity, which resulted in exhaustion in ~5 min (28). Although the explanation for this difference is not entirely clear, it may reflect differences in the type of muscle actions involved. In contrast to running, cycling involves high levels of muscular tension, which could lead to occlusion of vessels, and consequently impede blood flow and oxygen delivery, delaying the $\dot{V}O_2$ response. Running, on the other hand, has periods of low force production (e.g., when body is airborne), which should facilitate muscle blood flow and oxygen delivery, and consequently speed the $\dot{V}O_2$ response (17). However, if muscle O_2 availability was reduced during running compared with cycling, because of greater recruitment of muscle mass, this did not significantly affect τ_1. This outcome suggests that τ_1 is not altered significantly by the recruitment of a greater muscle mass, in contrast to $\dot{V}O_{2max}$. Runners would benefit more from a shorter duration of training intervals (~50 s), compared with cyclists (~70 s), whenever $\dot{V}O_{2max}$ training intensity is to be enhanced.

The absence of differences in absolute A_2 in-between exercise modes highlights some inconsistencies in the running and cycling literature (15,28,32), although no differences were reported between rowing and cycling (45). Regarding the relative A_2 (%A_2), our results do not support the literature where higher relative percentages of A_2 in cycling compared with running are well described (15,28,45). The explanation for the $\dot{V}O_2$ slow component is still a matter of debate and possibly influenced by muscle perfusion pressure and O_2 availability (15). In fact, the $\dot{V}O_2$ slow component is positively related to the amount of work that can be performed above the critical power intensity, and therefore, with the anaerobic energy contribution to exercise (33). The fact that our subjects, independent of the exercise mode performed, have a similar training background (in their respective speciality in which they compete) is suggestive of an equivalent anaerobic energy profile, depending similarly on this energy pathway at 100%$\dot{V}O_{2max}$ intensity. We interpret

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our results to indicate either that muscle O_2 availability to active muscle was well preserved in all exercise modes or that any reduction in O_2 availability did not measurably affect the amplitude of the $\dot{V}O_2$ slow component.

The positive relationship between $\dot{V}O_{2max}$ and Tlim-100%$\dot{V}O_{2max}$ in the square wave transition exercises reflects the dependency that the time sustained has on the underlying $\dot{V}O_{2max}$ irrespective of the mode of exercise. Although mechanical differences between exercise modes had a potential effect on the $\dot{V}O_2$ kinetics response, the same physiological response ($\dot{V}O_{2max}$) was observed at Tlim-100%$\dot{V}O_{2max}$. In fact, the subjects who reached higher $\dot{V}O_{2max}$ values were the ones that reached exhaustion at a later time. Thus, the Tlim-100%$\dot{V}O_{2max}$ does not depend solely on the $\dot{V}O_{2max}$ reached during the incremental protocol but instead is linked to the $\dot{V}O_{2max}$ reached in the square wave transition exercises. Previous studies reported a negative correlation between both parameters in running (4), swimming (3,26), and other exercise modes (5,24). However, the poor correlation between $\dot{V}O_{2max}$ and Tlim-100%$\dot{V}O_{2max}$ was previously reported for running and swimming (9,25).

In conclusion, when comparing the pulmonary and metabolic responses between the different exercise modes, no substantial differences were observed between the incremental and square wave protocols at an intensity requiring 100% of $\dot{V}O_{2max}$ intensity. However, the swimmers exhibited lower pulmonary and metabolic values compared with the other exercise modes, at both submaximal and maximal intensities. For the incremental protocol, the slopes of the regression lines of $E_{tot\text{-}inc}$ and workload steps showed that the cyclists had the greater rise in the slope and the swimmers a lower slope. The maximal exercise time at 100%$\dot{V}O_{2max}$ intensity and the $E_{tot\text{-}tlim}$ of all the four exercise modes was similar, although the swimmers had a higher Ana_{alac} energy contribution compared with the other exercise modes. The kinetics profile was characterized by lower A_1 values in the swimmers and a slower $\dot{V}O_2$ response compared with the other exercise modes. Moreover, the runners exhibited a faster $\dot{V}O_2$ response compared with cyclists. Although the $\dot{V}O_2$ slow component was observed in all exercise modes, no substantial differences in A_2 values among them was evident. Swimmers presenting a slower $\dot{V}O_2$ kinetics compared with the other exercise modes would benefit more from a longer duration (~90 s) of each set of exercise or intervals in the intermittent $\dot{V}O_{2max}$ training work, as well as cyclists (~70 s), in comparison with runners (~50 s). In addition, coaches should consider the time sustained at each exercise mode (200 s for swimming and rowing and 250 s for running and cycling) to specify the duration of work intervals at 100%$\dot{V}O_{2max}$ intensity.

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There was no reported conflict of interest.

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