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High-intensity Interval Training in Different Exercise Modes: Lessons from Time to Exhaustion

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ABSTRACT

To provide information for high-intensity interval training (HIIT) load, we compared the temporal variables of VO_2 response at, and after, a time sustained at the exercise intensity corresponding to VO_{2max} (Tlim) in different exercise modes. Forty-five trained male swimmers (11), rowers (13), runners (10) and cyclists (11) completed an incremental protocol to determine the velocity (vVO_{2max}) or power (wVO_{2max}) at VO_{2max} and a square wave exercise from rest to 100 % of vVO_{2max}/wVO_{2max}. The temporal variables of VO_2 response were examined using a breath-by-breath gas analyzer. VO_2 responses were not different between exercise modes, except for the percentage of VO_{2max} at 50 % of Tlim, which was ~6 % higher in rowing compared to cycling (97.70 ± 2.90 vs 92.40 ± 5.69 %, $p = 0.013$). During the recovery period, both swimmers and rowers evidenced higher percentages of VO_{2max} compared to cyclists at 30 s (65.1 ± 10.4 and 65.7 ± 5.6 vs 52.7 ± 5.6 %) and 60 s (41.7 ± 10.8 and 38.4 ± 5.4 vs 30.4 ± 1.8 %) time periods, all for $p < 0.01$. Furthermore, swimmers presented higher time values to reach 50 % VO_{2max} compared to runners and cyclists (51.1 ± 15.6 vs 38.1 ± 6.7 and 33.8 ± 4.7 %; $p < 0.001$). When training at 100 % of VO_{2max} intensity, fixed intervals for HIIT could be set freely. However, recovery periods based on time or intensity are exercise-mode dependent.

Introduction

It has been known for some time that maximal oxygen uptake (VO_{2max}) intensity can provide potentially valuable information about middle and long distance exercise [4]. Studies have focused on different strategies and training methods to improve athletes' aerobic performance [1], such as high-intensity continuous and interval training (HIIT) [21, 25]. The time sustained at the exercise intensity corresponding to VO_{2max} (Tlim) provides information on both aerobic and anaerobic fitness, helping to monitor the training effects and prescribe training loads [3]. In fact, the use of a fraction of Tlim has been used to establish HIIT for endurance athletes [16, 25], individualizing training prescription and enabling greater performance improvements.

Hill, Williams and Burt did not support the rationale of using 60 % of Tlim as an optimal interval duration to test the effects of high-intensity training on middle-distance runners [11].

In contrast, Smith et al. showed that velocities associated with VO_{2max} (vVO_{2max}), Tlim and 3000-m performance of trained middle distance runners increased after a 4-week training period when using the 60 % of Tlim criteria (better than when training at 70 % of Tlim) [26]. This conclusion was later extended to highly trained cyclists, in which 60 % of Tlim was shown to be an effective exercise interval duration for enhancing 40-km time trail performance [17, 18]. However, to improve the 2000-m rowing performance the 2.5-min high-intensity exercise duration seems to be widely used [8, 9], with the percentage of time regarding Tlim not being taken into consideration. In swimming, in contrast to the above-referred exercise modes, HITT is based on distance, with 50-m (~30-s) and 100-m (~60-s) repetitions used extensively, although no differences in VO_2 and heart rate (HR) responses were observed between distances [19].

Considering the similar values of Tlim among different exercises modes [27], it is expected that a fraction of this duration (as a way to provide greater improvement in aerobic fitness in each exercise mode) would be similar. However, the temporal variables of the VO_2 response of Tlim (i. e. the time of Tlim necessary to attain and time spent at specific percentages, as well as the percentage of VO_{2max} at specific temporal points of Tlim) have never been addressed in different exercise modes, still leaves unanswered whether 60 % (or other percentages) of Tlim interval duration would lead to similar ventilatory responses. In a similar manner, it has also been recommended that optimal improvement in cardiorespiratory performance should be done within the 90-100 % of VO_{2max} training range [23], with the time spent at ≥ 90 and 95 % of VO_{2max} as a key point to judge the effectiveness of the training stimulus [19, 22, 24]. Although this training method is well described in running-related literature, it has not been investigated in other exercise modes. The slower on- and off-transient VO_2 kinetics of swimming compared to other exercise modes [27, 28] and the higher VO_2 slow component in cycling compared to running [6, 15] suggest that this stimulus cannot be homogenously applied in different exercise modes.

Collectively, it is suggested that high-intensity training may be exercise-mode dependent, and therefore should not be applied equally to every cycle and individual sport. Otherwise, it could be misleading when establishing an appropriate HITT work duration or intensity. The knowledge concerning these variables will enable coaches to design better training programs aimed at the relevant improvements in endurance performance. The purpose was to compare the temporal variables of the VO_2 response at Tlim in swimming, rowing, running and cycling. In addition, as the recovery period in relation to HITT frequently diverges [20], we also compared the VO_2 responses of the different exercise modes after Tlim exercises. It was hypothesized that the temporal variables of the VO_2 responses at and after Tlim effort are distinct between exercise modes.

Material and Methods

Participants

Forty-five highly trained competitive male swimmers (n = 11; 18.8 ± 4.4 yrs-old, 1.79 ± 0.07 m; 70.7 ± 6.1 kg and 60.8 ± 5.1 ml.kg^{-1}.min^{-1}), rowers (n = 13; 26.3 ± 6.1 yrs-old, 1.78 ± 0.04 m, 73.6 ± 2.3 kg and 66.2 ± 4.2 ml.kg^{-1}.min^{-1}), runners (n = 10; 27.6 ± 4.1 yrs-old, 1.75 ± 0.07 m, 61.9 ± 6.4 m and 71.3 ± 4.1 ml.kg^{-1}.min^{-1}) and cyclists (n = 11; 24.9 ± 5.3 yrs-old, 1.77 ± 0.07 m, 69.6 ± 4.4 kg and 65.2 ± 5.2 ml.kg^{-1}.min^{-1}) (age, height, body mass and VO_{2max}, respectively) participated in the current study. All subjects had similar training background regarding competitive experience (~10 years) and hours of practice per week (12-14 h). All participants (or parent/guardians when subjects were under 18 years-old) provided informed written consent, and the study design was approved by the Institutional Review Board of the host university. All research was conducted ethically according to international standards, and as required by the International Journal of Sports Medicine [10].

Experimental Design

Subjects visited the testing facilities on two different occasions over a one-week period (with a minimum of 24-48 h between tests). In the first session, an intermittent incremental protocol, until exhaustion, for VO_{2max} and vVO_{2max} (swimming and running) or wVO_{2max} (rowing and cycling) assessment. The second session assessed Tlim, and consisted of a single square-wave transition exercise from rest to the previously determined vVO_{2max} or wVO_{2max} intensities, until volitional exhaustion. See Sousa et al. for more details about both protocols [27].

Methodology

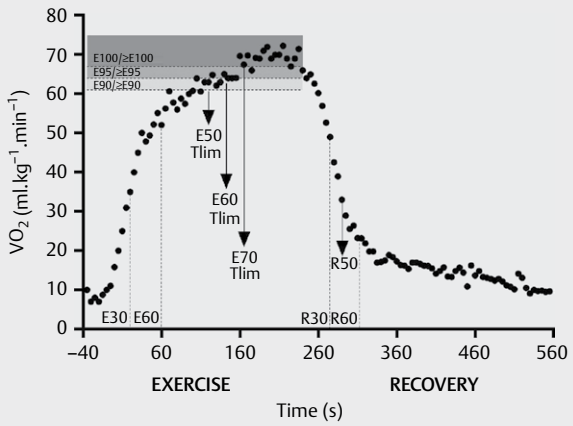
Respiratory and pulmonary gas-exchange variables were continuously measured using a telemetric portable breath-by-breath gas analyzer (K4b^2, Cosmed, Rome, Italy), which was calibrated according to manufacturing settings. VO_{2max} was considered to be reached according to primary and secondary criteria [14], and, together with VO_{2peak} (maximum VO_2 mean values reached during the square wave transition exercises, respectively) were measured over the last 60 s of exercise (in both protocols). Capillary blood samples (25 µL) for blood lactate ([La-]) were collected from the earlobe immediately at the end of the square wave transition exercises at 1, 3, 5 and 7 min of the recovery period, until maximal values were reached ($[La-]_{peak}$) (Lactate Pro, Arkay, Inc., Kyoto, Japan).

Data analysis

Occasional VO_2 breath values were omitted from the analysis by including only those between VO_2 mean ± 4 standard deviations, and after, smoothed by using a 3-breath moving average and 5 s time-averaged (Cosmed analysis software [7]). The VO_2 temporal variables considered during the square-wave transition exercises were: (i) the percentage/time of total Tlim spent to attain 90, 95 and 100 % VO_{2max} (E90, E95 and E100, respectively); (ii) the percentage/time of total Tlim spent at intensities ≥ 90, 95 and 100 %VO_{2max} (≥ E90, ≥ E95 and ≥ E100, respectively); (iii) the percentage of VO_{2max} at 30 and 60 s time period (E30 and E60); and (iv) the percentage of VO_{2max} at 50, 60 and 70 % of Tlim (E50-Tlim, E60-Tlim and E70-Tlim); and during the recovery period: (i) the time necessary to achieve 50 % VO_{2max} (R50); (ii) the percentage of VO_{2max} at 30 s time period (R30), and (iii) the percentage of VO_{2max} at 60 s time period (R60) (cf. ▶ **Fig. 1**).

Statistical Analysis

A Shapiro-Wilk test confirmed data normality and homogeneity, which was presented as mean ± SD. Differences between intermittent incremental protocols and square-wave transition exercises were tested with the paired sample T-Test. Differences between exercise modes were tested using a one-way ANOVA and explored further using Tukey's HSD post hoc procedure. Correlations between all variables were assessed via Pearson's product-moment correlation coefficient. Magnitudes of standardized effects (f and η^2) were determined against the following criteria: small, 0.2–0.5; moderate, 0.5–0.8, and large, >0.8. All statistical procedures were conducted with SPSS 21.0 and the significance level was set at 5 %.



▶ **Fig. 1** A representative VO_2/ time curve in one exercise mode with the corresponding temporal variables analyzed during exercise periods (percentage/time of total Tlim spent to attain and spent above 90 %, 95 % and 100 % of VO_{2max}: E90, E95 and E100, and, ≥E90, ≥E95 and ≥E100, respectively; percentage of VO_{2max} at 30 s and 60 s: E30 and E60; percentage of VO_{2max} at 50 %, 60 % and 70 % of Tlim: E50-Tlim, E60-Tlim and E70-Tlim) and recovery periods (time necessary to achieve 50 % VO_{2max}: R50; percentage of VO_{2max} at 30 s: R30; percentage of VO_{2max} at 60 s: R60).

Results

VO_{2max} was substantially different between exercise modes, with swimmers presenting ~8 and ~15 % lower values than rowers and runners ($p < 0.001$, $f = 0.39$), with this latter group exhibiting ~8 % higher values than cyclists. Tlim did not statistically differ between exercise modes (201.6 ± 28.1, 208.1 ± 28.1, 230 ± 23.7 and 208.0 ± 34.7 s, for swimming, rowing, running and cycling, respectively; $f = 0.08$) and no differences were found between VO_{2max} and VO_{2peak} for each exercise mode (< 2 % for all). However, VO_{2peak} values were ~16, ~12 and ~11 % higher for runners than swimmers, rowers and cyclists (respectively; $p < 0.001$, $\eta^2 = 0.39$). The $[La^-]_{peak}$ was ~30 % lower in swimming compared to the other three exercise modes ($p = 0.001$, $\eta^2 = 0.34$). ▶ **Table 1** shows the VO_2 response temporal variables (mean ± SD) during the square-wave transition exercises in each exercise mode.

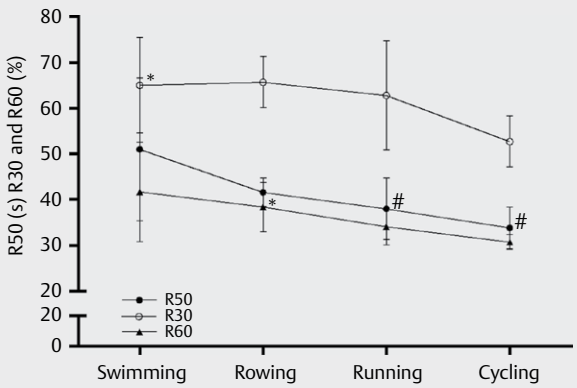
VO_2 responses during all square-wave transitions were not different between exercise modes for any of the temporal variables considered, with the exception of E50-Tlim that was ~6 % higher in rowing compared to cycling ($p = 0.013$, $\eta^2 = 0.23$).

During the recovery period (▶ **Fig. 2**), swimmers and rowers evidenced higher R30 ($p = 0.004$, $f = 0.27$) and R60 ($p = 0.01$, $f = 0.32$) compared to cyclists, and no differences were found between other exercise modes. Moreover, swimmers also exhibited higher values

▶ **Table 1** Temporal variables obtained during all square-wave transition exercises in each exercise mode (mean ± SD). * Significantly different than rowing ($p < 0.05$).

Temporal variables		Swimming	Rowing	Running	Cycling
E90	(%)	30.8 ± 8.1	28.4 ± 10.2	22.1 ± 8.9	30.5 ± 17.1
	(s)	60.0 ± 23.9	53.5 ± 18.4	53.0 ± 21.1	55.9 ± 20.6
E95	(%)	44.3 ± 8.8	47.6 ± 14.5	37.7 ± 12.7	44.5 ± 14.8
	(s)	87.7 ± 34.4	91.5 ± 22.7	90.0 ± 26.2	81.4 ± 33.7
E100	(%)	57.0 ± 13.5	49.8 ± 12.6	47.1 ± 17.7	47.8 ± 18.9
	(s)	108.0 ± 31.7	111.7 ± 24.0	112.5 ± 22.0	107.9 ± 36.3
≥E90	(%)	69.19 ± 8.11	71.6 ± 12.19	77.9 ± 9.0	69.5 ± 17.1
	(s)	145.3 ± 23.7	153.0 ± 35.87	157.6 ± 44.4	151.7 ± 54.6
≥E95	(%)	55.7 ± 8.8	52.4 ± 14.9	62.2 ± 12.7	55.5 ± 15.8
	(s)	117.5 ± 21.2	114.9 ± 30.9	140.0 ± 31.8	126.3 ± 33.8
≥E100	(%)	42.9 ± 13.5	49.8 ± 12.6	52.1 ± 7.7	47.8 ± 18.9
	(s)	95.1 ± 28.1	111.2 ± 36.5	124.3 ± 16.4	116.7 ± 41.9
E30	(%)	76.0 ± 8.0	78.2 ± 6.0	78.3 ± 7.7	77.5 ± 6.0
E60	(%)	89.4 ± 7.8	90.8 ± 5.1	89.4 ± 4.1	91.5 ± 5.2
E50-tlim	(%)	94.1 ± 3.0	97.7 ± 2.9	94.8 ± 2.9	92.4 ± 5.7 *
E60-tlim	(%)	97.8 ± 2.7	98.4 ± 2.7	97.2 ± 2.0	97.3 ± 2.7
E70-tlim	(%)	100.7 ± 2.0	100.1 ± 2.2	99.4 ± 1.8	99.5 ± 3.9

E90, 95 and 100 = percentage/time of total Tlim spent to attain 90, 95 and 100 % of VO_{2max}, respectively; ≥E90, 95 and 100 = percentage/time of total Tlim spent at intensities ≥90, 95 and 100 % of VO_{2max}, respectively; E30, and 60 = percentage of VO_{2max} at 30 and 60 s time period; E50-tlim, 60-tlim and 70-tlim = percentage of VO_{2max} at 50, 60 and 70 % of Tlim, respectively.



▶ **Fig. 2** Mean (± SD) of the time necessary to achieve 50 % VO_{2max} (R50; full circle), the percentage of VO_{2max} at 30 s time period (R30; open circle), and the percentage of VO_{2max} at 60 s time period (R60; triangle) during the recovery period after the square-wave transition exercises in swimming, rowing, running and cycling. Significant differences between cycling * and swimming # ($p \leq 0.05$).

for the R50 variable ($p < 0.001$, $f = 0.36$) compared to runners and cyclists, with no differences found between other exercise modes.

A moderate relationship between VO_{2max} and R50 ($r = -0.30$, 95 % CI: −1.08: −0.1, $p = 0.003$), and R60 ($r = -0.32$, 95 % CI: −0.78: −0.03, $p = 0.034$) for all groups combined were found. Although these relationships were not evident within each exercise mode, they did not lose their significance when the time sustained variable was controlled for partial correlation: $r = -0.30$, $p = 0.045$ and $r = -0.31$, $p = 0.035$ for R50 and R60, respectively.

Discussion

The current study was the first that compared the temporal variables of the VO_2 response at Tlim exercise in swimming, rowing, running and cycling, aiming to better specify training programs that will lead to improvements in endurance performance. Our main findings were that VO_2 responses during all square-wave transitions were not different between exercise modes for any of the temporal variables considered, with the exception of E50-Tlim that was higher in rowing compared to cycling. In contrast, VO_2 responses during the recovery period seems to be dependent on the exercise mode performed, since both swimmers and rowers evidenced higher R30 and R60 compared to cyclists, and swimmers exhibited higher R50 compared to runners and cyclists. Moreover, subjects who presented higher mean VO_{2max} values were the ones that recover faster, independently of the performed exercise mode.

The rationale for using vVO_{2max} and wVO_{2max} in exercise prescription is that it corresponds to the lowest velocity/power at which VO_{2max} is elicited in an incremental test, providing thus a fundamental intensity to develop athletes' maximal aerobic capacity [13]. In the current study, all subjects reached their VO_{2max} during the square-wave transition exercises performed at 100 % of VO_{2max} until exhaustion. In an attempt to determine the running velocity associated with the longest time sustained at the VO_{2max} intensity, Billat, Blondel and Berthoin [2] conducted all-out runs near this latter intensity – 90, 100, 120 and 140 %, reporting that the time sustained at VO_{2max} intensity was almost trivial (i. e. less than 20 s on average) at the 90 and 140 % conditions. However, it reached substantially higher values at the 100 % intensity (190 ± 87 s), confirming that 100 % condition was, in fact, the intensity associated with the longest time sustained at the VO_{2max} intensity.

Comparing the above-mentioned data with our study, although the absolute values sustained at 100 % of VO_{2max} were clearly lower for each exercise mode, the relative ones were not different (~48 %). In another study conducted with former male runners, Hill, Williams and Burt [11] reported that a total Tlim time of 166 s (~50 %) and 299 s (~90 %) were needed (performed at 100 % of VO_{2max} intensity) to reach 95 and 100 % of VO_{2max} intensities, respectively. Conversely, the time spent at intensities ≥ 95 and 100 % were 50 % (164 s) and 10 % (32 s), respectively. Their relative values for the 95 % of VO_{2max} intensity are closer to ours (~44 and ~56 % of Tlim total time to reach and spent, respectively), but our subjects needed only ~50 % of Tlim total time to reach 100 % of VO_{2max} intensity. If we take into account that the time constant parameter describes the rate at which VO_2 rises toward the steady state (1x time constant ~ to 63 %), the differences found for the 100 % of VO_{2max} intensity could be related with the VO_2 kinetics profile of the subjects.

The lack of differences in temporal variables between exercise modes in the current study was not an expected outcome, at least for the higher intensities (95 and 100 % of VO_{2max}). Despite using a similar sample, Sousa et al. [27] reported that VO_2 kinetics profile differed between distinct individual and cycle sports, with swimmers exhibiting a higher time constant (slower VO_2 kinetics) compared to rowers, runners and cyclists also on a square-wave exercise performed at 100 % of VO_{2max} intensity until exhaustion. In addition, these authors observed that runners, compared to cyclists, had faster VO_2 kinetics, a fact already reported during an exercise intensity, which resulted in exhaustion in ~5 min [12]. Thus, it would be expected that VO_2 response temporal variables would reflect the VO_2 kinetics differences among these exercise modes. In this matter, it might be that the variability associated with temporal variables is higher compared to that related to VO_2 kinetics parameters. In fact, it was previously suggested to use an individualized fraction of Tlim based on the VO_2 kinetics as a valid alternative for individualized parameters [22].

As an alternative to fixed long-interval durations, the 50–70 % of Tlim at VO_{2max} intensity has been suggested for individualizing interval training (cf. Buchheit and Laursen [5] for review) and between 60 and 75 % of Tlim have been used as the ideal exercise durations for interval training program optimization in trained cyclists [17, 18] and runners [26]. Although the influence of different HITT programs in VO_{2max} and time trial performance was examined before, the ventilatory responses between cycling and running was never reported, hindering a full understanding of this topic. In fact, Hill, Williams and Burt [11] reported that all examined runners did not attain VO_{2max} during the first 60 % of Tlim at an intensity corresponding to VO_{2max}, concluding that there was not a physiological rationale for prescribing exercise with those characteristics. In contrast, Laursen, Shing, Peake et al. [17] showed that when HIIT

incorporates VO_{2max} and 60 % of Tlim as the interval intensity and duration, respectively, highly trained cyclists could significantly improve their 40-km time trial performance. In the present study, no differences were found between exercise modes, suggesting that the E50, 60 and 70-Tlim intensities could be used freely in each exercise mode for HITT prescription. Moreover, in the current study, VO_{2max} was not attained at 50 or 60 % of the exhaustive efforts at VO_{2max} intensity, but only at 70 % of Tlim (in all exercise modes). Nevertheless, intensities ≥ 90 % of VO_{2max} were achieved even in the E50-Tlim variable. Considering that an optimal improvement in cardiorespiratory fitness performance relies on training at intensities corresponding to 90-100 % of VO_{2max} [23], the current data support a physiological rationale for prescription of HITT at VO_{2max} intensity for 50 ≤ Tlim ≤ 70 % durations, independently of the exercise mode performed.

Similarly to the 50–70 % of Tlim strategies, the 30 s interval has been used as an personalized work period in cycling [17, 18] and swimming [19]. In our study, no differences were found between exercise modes, as the E30 variable elicited similar VO_{2max} intensities (~77 %). We also observed that the E60 variable did not imply differences among exercise modes, corroborating that swimming sets of the same VO_{2max} intensity overall time (but with different work-interval durations, 30 s and 60 s) led to similar VO_2 responses [19].

These authors also showed that the time spent swimming above 95 % of VO_{2max} was doubled when using longer intervals compared to shorter ones, which is confirmed by the current study as the relative percentage of VO_{2max} elicited from the 60 s interval period (90 %) is higher than the 30 s one. As the 90 % (and 95 and 100 %) of VO_{2max} has been recommended as a training intensity that promotes an optimal improvement in cardiorespiratory fitness performance [23], we suggest that the 60 s, but not the 30 s parameter, could be used, independently of the exercise mode performed, as an alternative for using other fixed long-interval durations in HIIT.

The recovery time frequently suggested in HIIT tends to diverge [20], but it seems important to maintain a moderately high VO_2, allowing its maximum to be reached in a relatively short time during the subsequent work. Thus, exercise should start from an elevated VO_2 baseline [5], without selecting an exaggerated intensity that could elicit premature exhaustion [20]. The recovery time may also be gauged by the attainment of a particular recovery HR value, as a percentage of maximum HR [29]. Although HR was not analyzed in the current study, we verified that swimmers needed more time to achieve 50 % of VO_{2max} compared to runners and cyclists ($f = 0.36$) in the recovery period (higher R50). This fact may be justified by either a slower VO_2 off-kinetics, or by lower VO_{2max} values at this particular exercise. In fact, an inverse relationship was found between the R50 variable and VO_{2max} (explaining at least 10 % of the variance), which suggests that subjects with lower cardiorespiratory capacity need more time to recover. This fact enhances the idea that recovery time should be used differently in each exercise mode, as elicits different VO_{2max} percentages. Although not within the scope of this study, the 90 % variance in R50 might be related with VO_2 kinetic parameters, as shown previously [28]. Previous studies have also used a recovery time normally ranging from 15 s to 1 min [20]. In our study, both swimmers and rowers (compared to runners and cyclists) presented higher VO_{2max} percentages at 30 s and 60 s time periods ($f = 0.27$ and $f = 0.32$, respectively). Moreover, a negative relationship was found between R60 parameter and VO_{2max}.

The continuous exercise work analyzed, with its conclusions suggested to be applied when repeated intervals are performed, must be acknowledged as a limitation of this study. Therefore, the transitions between recovery-exercise within the same set could be influenced by the elevated baseline of the previous repetition, and consequently, implying less absolute time to achieve the target intensities. This must be taken into account, especially by coaches.

In conclusion, VO_2 responses during all of the square-wave transition exercises studied did not differ between exercise modes for the temporal variables considered (excepting E50-Tlim which was higher in rowing than cycling). However, swimmers and rowers (compared to cyclists) evidenced higher percentages of VO_{2max} at E30 and E60 s, and swimmers exhibited 50 % higher VO_{2max} values (compared to runners and cyclists). Last but not least, subjects who presented higher mean VO_{2max} values were the ones that recovered faster, independent of the exercise mode.

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Conflict of Interest

The authors declare that they have no conflict of interest.

References

[1] Bertuzzi R, Bueno S, Pasqua LA, Acquesta FM, Batista MB, Roschel H, Kiss MA, Serrão JC, Tricoli V, Ugrinowitsch C. Bioenergetics and neuromuscular determinants of the time to exhaustion at velocity corresponding to VO2max in recreational long-distance runners. J Strength Cond Res. 2012; 26: 2096–2102

[2] Billat V, Blondel N, Berthoin S. Determination of the velocity associated with the longest time to exhaustion at maximal oxygen uptake. Eur J Appl Physiol 1999; 80: 159–161

[3] Billat V, Renoux J, Pinoteau J, Petit B, Koralsztein J. Times to exhaustion at 90, 100 and 105 % of velocity at VO2max (maximal aerobic speed) and critical speed in elite long distance runners. Arch Physiol Biochem 1995; 103: 129–135

[4] Billat VL, Koralsztein J. Significance of the velocity at VO2max and time to exhaustion at this velocity. Sports Med 1996; 22: 90–108

[5] Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle. Sports Med 2013; 43: 313–338

[6] Carter H, Jones AM, Barstow TJ, Burnley M, Williams CA, Doust JH. Oxygen uptake kinetics in treadmill running and cycle ergometry: A comparison. J Appl Physiol 2000; 89: 899–907

[7] de Jesus K, Guidetti L, de Jesus K, Vilas Boas JP, Baldari C, Fernandes R. Which Are The Best VO2 Sampling Intervals to Characterize Low to Severe Swimming Intensities? Int J Sports Physiol Perform 2014; 35: 1030–1036

[8] Driller MW, Fell JW, Gregory JR, Shing CM, Williams AD. The effects of high-intensity interval training in well-trained rowers. Int J Sports Physiol Perform 2009; 4: 110–121

[9] Driller MW, Gregory JR, Williams AD, Fell JW. The effects of chronic sodium bicarbonate ingestion and interval training in highly trained rowers. Int J Sport Nutr Exerc Metab 2013, doi:40–47

[10] Harriss DJ, Macsween A, Atkinson G. Standards for ethics in sport and exercise science research: 2018 update. Int J Sports Med 2017; 38: 1126–1131

[11] Hill D, Williams C, Burt S. Responses to exercise at 92 % and 100 % of the velocity associated with VO2max. Int J Sports Med 1997; 18: 325–329

[12] Hill DW, Halcomb JN, Stevens EC. Oxygen uptake kinetics during severe intensity running and cycling. Eur J Appl Physiol 2003; 89: 612–618

[13] Hill DW, Rowell A. Responses to exercise at the velocity associated with VO2max. Med Sci Sports Exerc 1997; 29: 113–116

[14] Howley ET, Bassett DR, Welch HG. Criteria for maximal oxygen uptake: Review and commentary. Med Sci Sports Exerc 1995; 27: 1292–1301

[15] Jones AM, McConnell AM. Effect of exercise modality on oxygen uptake kinetics during heavy exercise. Eur J Appl Physiol 1999; 80: 213–219

[16] Laursen PB, Jenkins DG. The scientific basis for high-intensity interval training. Sports Med 2002; 32: 53–73

[17] Laursen PB, Shing CM, Peake JM, Coombes JS, Jenkins DG. Interval training program optimization in highly trained endurance cyclists. Med Sci Sports Exerc 2002; 34: 1801–1807

[18] Laursen PB, Shing CM, Peake JM, Coombes JS, Jenkins DG. Influence of high-intensity interval training on adaptations in well-trained cyclists. J Strength Cond Res 2005; 19: 527–533

[19] Libicz S, Roels B, Millet G. VO2 responses to intermittent swimming sets at velocity associated with VO2max. Can J Appl Physiol 2005; 30: 543–553

[20] Midgley A, McNaughton L. Time at or near VO2max during continuous and intermittent running: A review with special reference to considerations for the optimisation of training protocols to elicit the longest time at or near VO2max. J Sports Med Phys Fitness 2006; 46: 1–14

[21] Midgley A, McNaughton L, Carroll S. Physiological determinants of time to exhaustion during intermittent treadmill running at vVO2max. Int J Sports Med 2007; 28: 273–280

[22] Millet GP, Candau R, Fattori P, Bignet F, Varray A. VO2 responses to different intermittent runs at velocity associated with VO2max. Can J Appl Physiol 2003; 28: 410–423

[23] Robinson DM, Robinson SM, Hume PA, Hopkins WG. Training intensity of elite male distance runners. Med Sci Sports Exerc 1991; 23: 1078–1082

[24] Rønnestad BR, Hansen J. Optimizing interval training at power output associated with peak oxygen uptake in well-trained cyclists. J Strength Cond Res 2016; 30: 999–1006

[25] Rozenek R, Funato K, Kubo J, Hoshikawa M, Matsuo A. Physiological responses to interval training sessions at velocities associated with VO2max. J Strength Cond Res 2007; 21: 188–192

[26] Smith TP, McNaughton LR, Marshall KJ. Effects of 4-wk training using Vmax/Tmax on VO2max and performance in athletes. Med Sci Sports Exerc 1999; 31: 892–896

[27] Sousa A, Figueiredo P, Zamparo P, Pyne DB, Vilas-Boas JP, Fernandes RJ. Exercise Modality Effect on Bioenergetical Performance at VO2max Intensity. Med Sci Sports Exerc 2015; 47: 1705–1713

[28] Sousa A, Rodríguez F, Machado L, Vilas Boas JP, Fernades R. Exercise modality effect on VO2 off-transient kinetics at VO2max intensity. Exp Physiol 2015; 100: 719–729

[29] Vuorimaa T, Karvonen J. Recovery time in interval training for increasing aerobic capacity. Ann Sports Med 1988; 3: 215–219