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ORIGINAL ARTICLE

The highest intensity and the shortest duration permitting attainment of maximal oxygen uptake during cycling: effects of different methods and aerobic fitness level

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Abstract The aims of this study were: (1) to verify the validity of previous proposed models to estimate the lowest exercise duration (T_{LOW}) and the highest intensity (I_{HIGH}) at which VO$_2$max is reached (2) to test the hypothesis that parameters involved in these models, and hence the validity of these models are affected by aerobic training status. Thirteen cyclists (EC), eleven runners (ER) and ten untrained (U) subjects performed several cycle-ergometer exercise tests to fatigue in order to determine and estimate T_{LOW} (ET_{LOW}) and I_{HIGH} (EI_{HIGH}). The relationship between the time to achieved VO$_2$max and time to exhaustion (T_{lim}) was used to estimate ET_{LOW}. EI_{HIGH} was estimated using the critical power model. I_{HIGH} was assumed as the highest intensity at which VO$_2$ was equal or higher than the average of VO$_2$max values minus one typical error. T_{LOW} was considered T_{lim} associated with I_{HIGH}. No differences were found in T_{LOW} between ER (170 ± 31 s) and U (209 ± 29 s), however, both showed higher values than EC (117 ± 29 s). I_{HIGH} was similar between U (269 ± 73 W) and ER (319 ± 50 W), and both were lower than EC (451 ± 33 W). EI_{HIGH} was similar and significantly correlated with I$_{HIGH}$ only in U ($r = 0.87$) and ER ($r = 0.62$). ET_{LOW} and T_{LOW} were different only for U and not significantly correlated in all groups. These data suggest that the aerobic training status affects the validity of the proposed models for estimating I_{HIGH}.

Keywords Oxygen uptake response · Aerobic training status · Severe-intensity domain

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Introduction

Exercise intensity domains have been defined based upon their distinct metabolic profiles (Gaesser and Poole 1996). The moderate intensity domain consists of work rates at or below the lactate threshold (LT). The heavy domain includes work rates above LT, but at or below critical power (CP). The severe intensity domain encompasses work rates above CP in which maximal oxygen uptake (VO$_2$max) can be elicited. In fact, in the severe domain VO$_2$ continues to increase over time until VO$_2$max is attained (Poole et al. 1988; Hill et al. 2002). Therefore, it is not possible for a subject to perform a constant work rate that provides a VO$_2$ equivalent to a particular percentage of the VO$_2$max. This means that VO$_2$max is not associated with a unique work rate, rather it is attained over a range of work rates. While the same value of VO$_2$ (i.e., VO$_2$max) is achieved regardless of exercise intensity within this domain, the time to achieve VO$_2$max (TAVO$_2$max) is inversely related to exercise intensity (Margaria et al. 1965; Hill et al. 2002).

Several studies have shown TAVO$_2$max is shorter at higher intensities for both cycling (Margaria et al. 1965; Hill et al. 2002) and running exercises (Hill et al. 1997; Billat et al. 2000). Thus, there should be a unique exercise intensity within the severe domain, at which VO$_2$max would be achieved momentarily at the point of fatigue or maintained for a few seconds. However, few studies have specifically sought to characterize VO$_2$ responses within this exercise domain with regard to the lowest exercise duration (T_{LOW}) or the highest intensity (I_{HIGH}) at which the VO$_2$max can still be reached. Recently, Hill et al. (2002) and Hill and Stevens (2005) have described in intensities within the severe intensity domain a linear relationship between TAVO$_2$max and its respective time to exhaustion (T_{lim}), in active individuals. In the work of Hill et al. (2002), using TAVO_2max expressed as a function of T_{lim}, it was possible to estimate T_{LOW} (ET_{LOW}) (the unique T_{lim} at which VO_2max is achieved at the point of fatigue, where, i.e., TAVO_2max = T_{lim}, see the upper panel in Fig. 1). The power associated with ET_{LOW}, was considered as an estimative of I_{HIGH} (EI_{HIGH}), by using the two-parameter hyperbolic power–T_{lim} relationship (see the lower panel in Fig. 1), so called of Critical Power model (CP model) (Morton 2006). However, the authors did not directly validate the estimates by testing participants at and above their EI_{HIGH}. Thus, the actual assessment of I_{HIGH} and T_{LOW} from the VO_2 responses during the several short constant-load exercises performed at different intensities (a gold standard value) still remains to be done.

The advantages of using such models are based on the usefulness of a test protocol (e.g., 2–4 constant-load tests to establish simultaneously the relationships between power–T_{lim} and TAVO_2max–T_{lim}) that provides an estimate of both, the lowest and the highest exercise intensity at which VO_2max can be reached, along with other parameters of CP model, as the measurements of aerobic and anaerobic capacity. It would therefore be useful if a valid and reliable means of establishing these exercise intensities are available in a single test protocol.

In this way, some important aspects might be highlighted with regard to these two models utilized by Hill et al. (2002) for estimating T_{LOW} and I_{HIGH}. It can be hypothesized that the linear relationship between TAVO_2max and T_{lim} would be dependent on both, the speed of the VO_2 response, and the relationship between relative exercise intensity (e.g., percentage of VO_2max) and its respective T_{lim}. As TAVO_2max is determined by VO_2 kinetics, the individuals with faster VO_2 kinetics would be expected to achieve VO_2max faster, and therefore, would have a lower TAVO_2max. Additionally, differences in T_{lim} at a given relative intensity might also to modify the linearity and slope of relationship between TAVO_2max and T_{lim}. Some studies have reported that aerobic training may accelerates VO_2 kinetics and increase T_{lim} during cycling exercise at the intensity associated with VO_2max (Caputo et al. 2003; Caputo and Denadai 2004; Messonnier et al. 2004). Thus, it is likely that aerobic training status may influence the relationship between TAVO_2max and T_{lim}, and hence the estimative of T_{LOW}.

Regarding the CP model, extrapolation of the relationship to high exercise intensities requires that an infinitely high power output can be sustained for a very short time. Clearly, this requirement is not met in nature, and the two-parameter CP model may break down when T_{lim} is too low (e.g., T_{lim} = ET_{LOW}, see the lower panel in Fig. 1) (Bosquet et al. 2006; Hopkins et al. 1989; Morton 1996). Bosquet et al. (2006) have shown that critical velocity

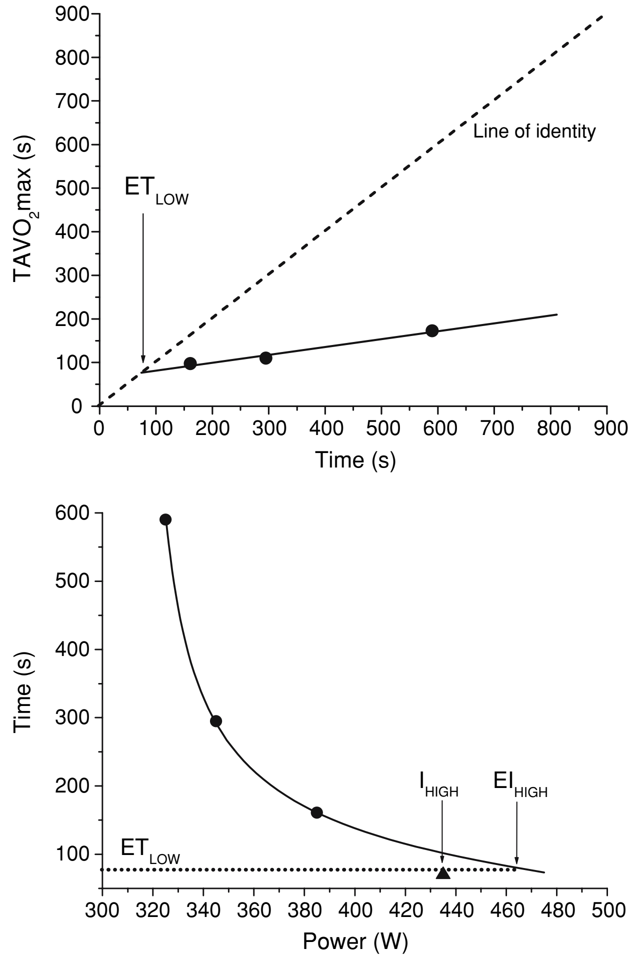

Fig. 1 Estimation of the lowest exercise duration (ET_{LOW}) and the highest exercise intensity (EI_{HIGH}) at which VO_2max can be attained. In the upper panel, ET_{LOW} (80 s) was estimated by solving for the time for which T_{lim} was equal to TAVO_2max, represented as the point of intersection between the T_{lim} and TAVO_2max regression line (*solid line*) and the line of identity (*dashed line*). In the *lower panel*, EI_{HIGH} was estimated as the intensity associated with ET_{LOW}, by using the two-parameter hyperbolic power–time relationship (*solid line*). *Triangle* is the highest exercise intensity (I_{HIGH} = 435 W) and its respective duration (72 s) at which VO_2max was attained, when directly determined. Data from a representative participant. See text for details

(extension of power–T_{lim} to velocity–T_{lim} model) determined by two-parameter hyperbolic model overestimated the real performance of exercise lasting ~136 s. In this way, as EI_{HIGH} is obtained from CP model by using ET_{LOW}, it is likely that the two-parameter CP model shows a limitation to estimate EI_{HIGH} when lower ET_{LOW} values are utilized. As stated above, the higher the aerobic fitness, the lower TAVO_2max, and consequently, the lower ET_{LOW}. In this scenario, it can be hypothesized that aerobic fitness level can differently affect the validity of these two models for estimating T_{LOW} and I_{HIGH}.

Therefore, the main purpose of the present study was to verify the validity of the linear relationship between

TAVO_2max and T_{lim} to estimate T_{LOW} and of the CP model to estimate I_{HIGH}, by direct determining I_{HIGH} and T_{LOW}. The second aim was to test the hypothesis that both, TAVO_2max and T_{lim} relationship and CP model might be affected by aerobic training status through a cross-sectional analysis. Since endurance runners exercising on cycle-ergometer show a moderate aerobic fitness (Caputo and Denadai 2004), they were studied as an intermediate aerobic fitness group between trained and untrained subjects.

Methods

Subjects

Ten untrained males (*U*) (24.4 ± 3.3 year; 74.4 ± 11.8 kg; 175.3 ± 5.4 cm), thirteen endurance cyclists (EC) (25.6 ± 4.5 year; 67.9 ± 7.2 kg; 175.6 ± 5.1 cm), 11 endurance runners (ER) (27.2 ± 8.9 year; 64.6 ± 5.9 kg; 173.1 ± 5.6 cm) volunteered their written informed consent to participate in the study. The study was performed according to the Declaration of Helsinki and the protocol was approved by the São Paulo State University's Ethics Committee. ER had been competing for 4.2 ± 2.3 year and EC for 9.7 ± 4.3 year. Mean training distances (km) a week were 105 ± 34 for ER and 403 ± 145 for EC. The current 5 km time trials for ER were 1,025 ± 76 s. The subjects were asked not to train hard during the last 2 days before each test and to report to the laboratory at least 3 h after the last meal. The individuals in U group might be involved in recreational activities (e.g., soccer, jogging, and tennis) but all have not been engaged in any form of aerobic training.

Experimental design

Subjects visited the laboratory for three stages of experimentation. (1) An incremental test to determine VO_2max and the intensity associated with the achievement of VO_2max (IVO_2max), (2) second stage involved three laboratory sessions to determine VO_2 kinetics (TAVO_2max), T_{lim}, CP model parameters, ET_{LOW} and EI_{HIGH}, with the subjects performing in random order constant work rate transitions from rest to one of three exercise intensities: 95, 100, 110% IVO_2max. (3) The third stage involved the determination of I_{HIGH} and T_{LOW} from two to four constant work rate tests to exhaustion. All tests were performed at the same time of day (±2 h) to minimize the effects of diurnal biological variation on the results (Carter et al. 2002). Subjects performed only one test on any given day and the tests were each separated by ≥48 h but completed within a period of 3–4 weeks.

Procedures

Materials

All exercise testing was conducted on a mechanically braked cycle ergometer (Monark 828E, Stockholm, Sweden). Pedal frequency was maintained at a constant 70 rpm for all cycle tests. Throughout the tests, the respiratory and pulmonary gas-exchange variables were measured using a breath-by-breath portable gas analyzer (Cosmed K4b^2, Rome, Italy). These analyzers have previously been validated over a wide range of exercise intensities (McLaughlin et al. 2001). Before each test, the O_2 and CO_2 analysis systems were calibrated using ambient air and a gas of known O_2 and CO_2 concentration according to the manufacturer's instructions, while the K4b^2 turbine flowmeter was calibrated using a 3-l syringe (Cosmed K4b^2, Rome, Italy). Heart rate (HR) was also monitored throughout the tests (Polar, Kempele, Finland). Breath-by-breath VO_2 and HR data were reduced to 15 s stationary averages in the incremental test for VO_2max determination (Data Management Software, Cosmed, Rome, Italy).

Incremental tests

Subjects performed incremental exercise (3-min stages) to volitional exhaustion to determine VO_2max and IVO_2max. The untrained subjects began the test at 35 W, runners at 70 W and the cyclists at 140 W, with increases in power of 35 W at each stage. At the end of each stage without interrupting the protocol an earlobe capillary blood sample was collected. Each subject was encouraged to give a maximum effort. The VO_2max was defined as the highest 15 s VO_2 value reached during the incremental test. All subjects fulfilled at least two of the following three criteria for VO_2max: (1) respiratory exchange ratio (RER) greater than 1.1; (2) a blood lactate concentration greater than 8 mM; and (3) peak HR at least equal to 90% of the age-predicted maximal (Taylor et al. 1955). The IVO_2max was defined as the power output at which VO_2max occurred (Faina et al. 1997).

Constant power tests

The subjects subsequently performed a series of constant work rate transitions at the three exercise intensities (95, 100, 110% IVO_2max) on separate days. The exercise protocol began with a 10 min warm-up at 50% IVO_2max followed by 5 min rest, after which the subjects were instructed to perform the required intensity until they were unable to maintain the fixed intensity. At the start of cycling exercise, the subjects pedaled against zero resistance, until a pedal cadence of

70 rpm was reached, at that point, the pre-selected work rate was imposed and timing began. The test was terminated when the subject could not maintain a cadence of >67 rpm despite of verbal encouragement. $T_{\lim}$ was measured to the nearest second. The transition from rest to exercise took <5 s. During the constant work rate tests the peak of VO_2 (VO_2peak) was defined as the highest 15 s average value.

Determination of CP

Individual values for power–$T_{\lim}$ from the constant work rate tests were fit to the hyperbolic model, using iterative nonlinear regression procedures on Microcal Origin 6.0 (Northampton, MA, USA):

$$T_{\mathrm{Lim}} = \mathrm{AWC} \cdot (\mathrm{power} - \mathrm{CP})^{-1}. \quad (1)$$

Values were derived for two parameters: CP, which is the power asymptote of the relationship, and AWC, which is the area bounded by CP, the x-axis, and any point on the power–time curve, and which represents the anaerobic work capacity (Barker et al. 2006). Regressions were also performed using the mathematically equivalent linear power–$T_{\lim}^{-1}$ and work–$T_{\lim}$ relationships. The parameters estimates (CP and AWC) were not significantly different between the mathematical models. Thus, for each participant, the parameter estimate generated using the hyperbolic model was used as the criterion measure (EC, SEE = 5.3 ± 5.7 and $R^2 = 0.98 \pm 0.03$; ER, SEE = 4.6 ± 3.1 and $R^2 = 0.97 \pm 0.02$; *U*, SEE = 6.0 ± 4.2 and $R^2 = 0.98 \pm 0.02$).

V*O*$_2$ *kinetics*

For each exercise transition, breath by breath VO_2 responses were fit to the following equation using iterative nonlinear regression procedures on Microcal Origin 6.0 (Fig. 2):

$$VO_2(t) = VO_{2\mathrm{b}} + A\left(1 - \mathrm{e}^{-(t/\tau)}\right) \quad (2)$$

where VO_2 (*t*) is oxygen uptake at time *t*, $VO_{2\mathrm{b}}$ is the pre-exercise VO_2; *A* is the asymptotic amplitude, and τ is the time constant of VO_2 kinetics (defined as the time required to attain 63% of the *A*). Occasional errant breath values were deleted from the data set if they fell more than four standard deviations outside the mean 30-s periods (Ozyener et al. 2001). The VO_2 was assumed to have essentially reached its maximal value when the value of $(1 - \mathrm{e}^{-(t/\tau)})$ from Eq. 2 was 0.99, (i.e., when $t = 4.6 \times \tau$) and it was assumed that the VO_2 was projecting to VO_2max. Therefore, for each test, TAVO_2max, was defined as $4.6 \times \tau$. Time maintained at VO_2max (TMVO_2max), was determined by subtraction of the TAVO_2max from $T_{\lim}$. We have showed that confidence

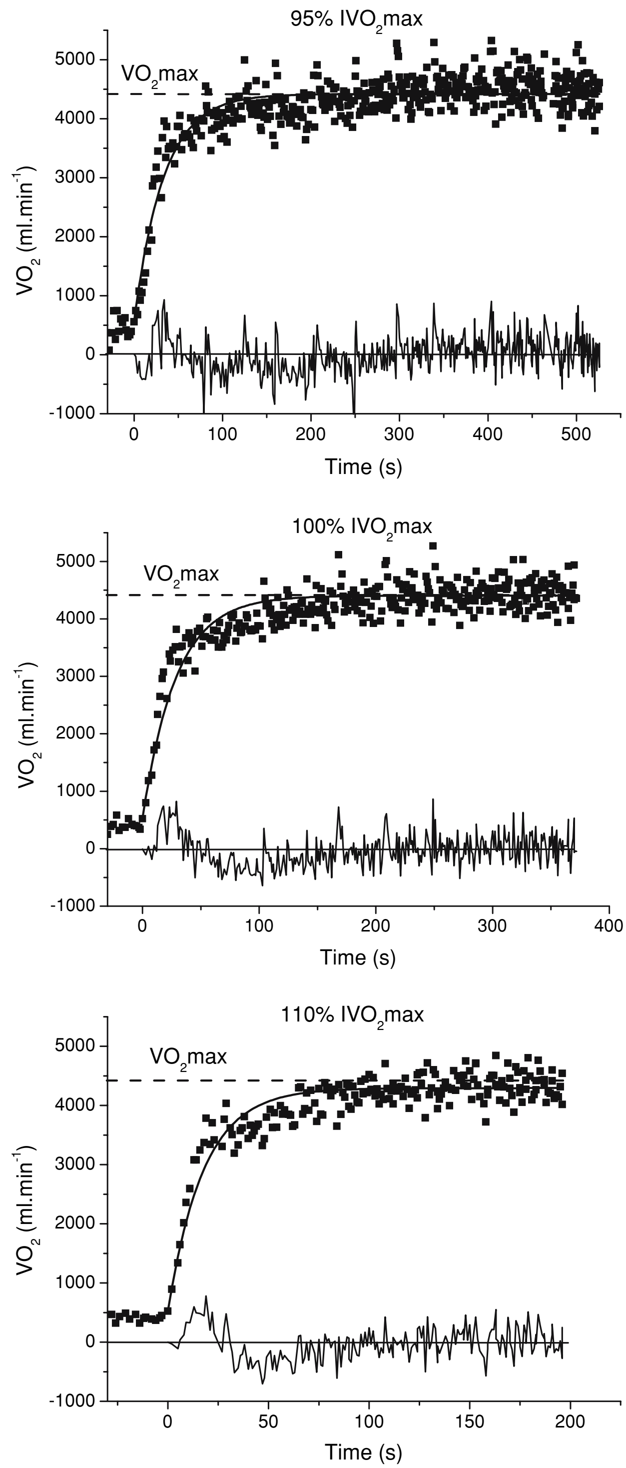

Fig. 2 Modeling of breath-by-breath VO_2 response to severe exercise (from *top* to *bottom*) at 95, 100 and 110% IVO_2max, respectively, for a representative subject, including the corresponding residual plots. *Dashed line* represents VO_2max obtained during incremental test. The *curves* were fitted by a mono-exponential function

intervals for τ estimation, which is based on oxygen uptake amplitude and the standard deviation of breath-by-breath fluctuations (Lamarra et al. 1987) were between ±2 and 5 s for one transition eliciting VO_2max in groups with different aerobic fitness levels (Caputo and Denadai 2004).

Estimation of ET_{LOW} *and* EI_{HIGH}

Linear regression techniques using Microcal Origin 6.0 were employed to describe individually the relationship between the TAVO_2max and T_{lim}. With TAVO_2max expressed as a function of T_{lim}, it was possible to solve for the unique T_{lim}, at which VO_2max might hypothetically be achieved momentarily at the exhaustion (ET_{LOW}), i.e., when TAVO_2max = T_{lim}. EI_{HIGH} was calculated using Eq. 1, utilizing ET_{LOW} instead of T_{lim} (Fig. 1).

Determination of T_{LOW} *and* I_{HIGH}

Subsequently, to determine directly I_{HIGH} and T_{LOW}, the subjects performed 2–4 further constant work rate tests to exhaustion. The work rate of the first test corresponded to EI_{HIGH}. If during the first constant work rate test VO_2max could be reach or maintained, further subsequent constant work rate tests at a 5% higher work rate were performed on separate days until VO_2max could not be reached. If during the first constant work rate test VO_2max could not be reach or maintained, further constant work rate tests were conducted with subsequently reduced work rate (5%). The I_{HIGH} was defined for each subject as the highest power output at which the highest 15-s VO_2 average determined from rolling averages of 5-s samples was equal or higher than VO_2max (averaging the highest VO_2 values from incremental and constant work rate tests) minus one typical error of measurement (TEM) (Fig. 3). TEM for VO_2max was calculated as the SD of the change score in the highest VO_2 values obtained during incremental and constant work rate tests divided by $\sqrt{2}$ (Hopkins 2000). T_{LOW} was T_{lim} performed at I_{HIGH}. Additionally, in order to test the validity of CP model for predicting a given exercise intensity or duration, predictions of I_{HIGH} and T_{LOW} were also calculated using CP model from the actual T_{LOW} and I_{HIGH} [i.e., predicted $I_{HIGH} = \mathrm{AWC} \times T_{LOW}^{-1} + \mathrm{CP}$ or predicted $T_{LOW} = \mathrm{AWC} \times (I_{HIGH} - \mathrm{CP})^{-1}$].

Statistics

Data are presented as mean ± SD. Normality of the distribution was checked by the Shapiro–Wilk's test. The effects of both aerobic training status (all variables) and exercise intensity (T_{lim} and TAVO_2max) were tested using one-way ANOVA, with Scheffé (training status) and Tukey (exercise intensity) post-hoc tests where appropriate. Student's paired

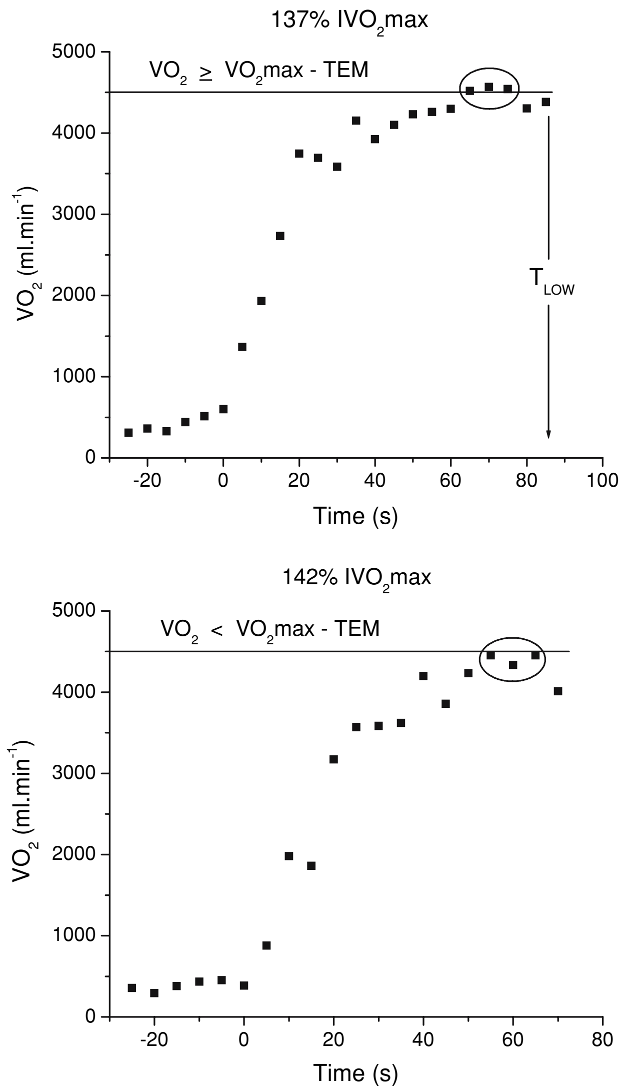

Fig. 3 Determination of I_{HIGH} and T_{LOW} for the same subject represented in Fig. 1. Individual data points are 5-s average values. VO_2max − TEM is VO_2max average from incremental and constant work rate tests minus one typical error of measurement (*TEM*). T_{LOW} is the time to fatigue. Note that only in the upper panel (137% IVO_2max) the highest 15-s VO_2 value (*open circle*) was equal or higher than VO_2max − TEM, satisfying the criterion for I_{HIGH} determination

t test and Pearson correlation coefficients were used to test the validity of the models for estimating I_{HIGH} and T_{LOW}. In addition, the typical error of estimate (TEE) was calculated (Hopkins, 2000). Significance was set at $P \leq 0.05$.

Results

Incremental tests

The mean values for VO_2max determined in the incremental test for ER were lower than EC and higher than *U*

Table 1 The highest VO_2 values (ml kg^{-1} min^{-1}) obtained in the different tests for untrained (U), runners (ER) and cyclists (EC)

Test	U (n = 10)	ER (n = 11)	EC (n = 13)
Incremental	42.9 ± 3.5^A	54.6 ± 5.5^B	63.3 ± 6.7^C
95%	45.6 ± 5.0^A	54.6 ± 4.1^B	63.3 ± 6.2^C
100%	43.7 ± 3.1^A	55.4 ± 5.9^B	63.9 ± 6.9^C
110%	43.1 ± 4.2^A	53.2 ± 5.7^B	62.5 ± 6.1^C
I_{HIGH}	43.2 ± 4.0^A	53.6 ± 4.6^B	62.5 ± 5.4^C
>I_{HIGH}	40.2 ± 3.1^A	48.6 ± 5.3^B	57.1 ± 7.2^C

Values are mean ± SD. 95, 100, 110%, are constant work rate tests performed, respectively, at 95, 100 and 110% of IVO_2max. > I_{HIGH}, constant work rate test performed at intensity just above I_{HIGH}

Means with the same superscript were not different

(Table 1). There were no significantly differences (P = 0.31) for IVO_2max between U (231 ± 45 W) and ER (257 ± 40 W), but both were lower (P < 0.001) than EC (348 ± 30 W).

Responses to the constant power tests

T_{lim} and TAVO_2max obtained during constant work rate tests at 95, 100 and 110% IVO_2max are presented in Fig. 4. T_{lim} values at 95% IVO_2max for EC were similar (P > 0.20) to ER and U. However, U showed lower (P = 0.04) values compared to ER. There were no differences for T_{lim} at 100 and 110% IVO_2max between the groups. For ER and U groups, TAVO_2max at 95, 100, 110% IVO_2max were not different (P > 0.09), but higher compared to EC (P < 0.03). With regard to exercise intensity, TAVO_2max were longer in the lower power tests in U (P < 0.05). However, in EC and ER TAVO_2max were different only between 95 and 110% IVO_2max (P < 0.02).

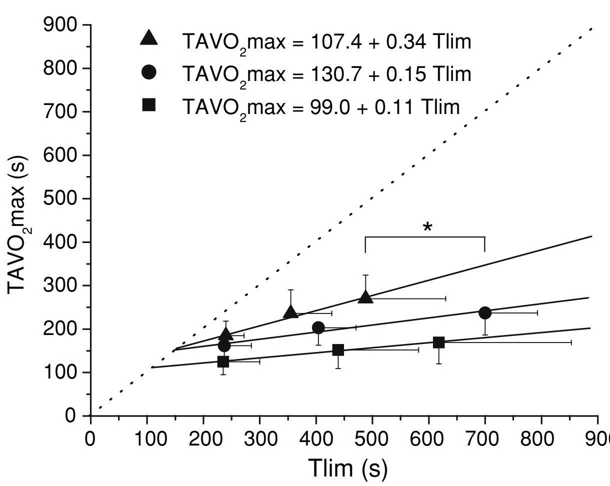

Fig. 4 Graphic representation of the relationship between T_{lim} and TAVO_2max. ET_{LOW} was determined by solving for the time for which T_{lim} = TAVO_2max, represented here as the point of intersection of the T_{lim} and TAVO_2max regression lines with the line of identify. The *dotted line* is the line of identify; *solid line* represents the regression equation for each group. *Filled triangle* represents U, *filled circle* represents ER, *filled square* represents EC. The regression equation is represented on legend for each group. Data are mean ± SD. *Significant difference for T_{lim} between U and ER

CP parameters

The mean value for CP was not different (P = 0.08) between U (182 ± 52 W) and ER (222 ± 34 W), but higher (P < 0.001) for EC (299 ± 30 W). The mean value for AWC was not different (P > 0.07) between the three groups (U = 17.4 ± 3.4 kJ; ER = 14.9 ± 2.8 kJ; EC = 19.7 ± 6.7 kJ).

Validity of the proposed models

The mean values for actual, estimated and predicted I_{HIGH} and T_{LOW} are reported in Table 2. There were no differences for I_{HIGH} (W) between U and ER (P = 0.18), but both were lower (P < 0.001) compared to EC. When I_{HIGH} was expressed as percentage of IVO_2max there were no differences between EC and ER (P = 0.29), but U was lower compared to EC (P = 0.02). T_{LOW} were lower (P < 0.001) in EC, but similar between U and ER (P = 0.18). EI_{HIGH} was similar (P > 0.17) and significantly correlated with I_{HIGH} only in U (r = 0.87, P = 0.01) and ER (r = 0.61, P = 0.04). The CP model also overestimated the predicted I_{HIGH} only for EC (P = 0.04). We found significant correlations between the bias (EI_{HIGH} − I_{HIGH}) and ET_{LOW} for all groups (U = −0.85, P = 0.02; ER = −0.83, P = 0.002; EC = −0.59, P = 0.03) (Fig. 5). For each group, the mean correlation between TAVO_2max and T_{lim} were of 0.84 ± 0.2, 0.85 ± 0.2 and 0.85 ± 0.2 for U, ER and EC, respectively. See Fig. 4 for a graphical representation of these relationships for each group. EI_{HIGH} and T_{LOW} were different only for U (P = 0.03), however, they were not significantly correlated for all groups.

The typical error of estimative (TEE) suggests a low validity of the models to estimate ET_{LOW} for U (15.6%) and ER (13.8%) but not for EC (7.2%). Higher values of TEE for ET_{LOW} suggested a very low validity of the TAVO_2max and T_{lim} relationship (15.3, 21.5 and 30.1% for U, ER and EC, respectively). The mean variability of the highest VO_2 obtained in incremental and constant work rate tests (95, 100, 110% IVO_2max) were not different between U [4.2 (0.5 − 8.4)%], ER [4.3 (1.6 − 6.8)%] and EC [3.4 (1.4 − 6.6)%], but there was a high variability within each group.

Table 2 Actual, estimated and predicted values for the lowest exercise time (T_{LOW}) and the highest absolute and relative intensity (I_{HIGH}) at which the VO_2max is reached for untrained (*U*), runners (ER) and cyclists (EC)

Variables	Groups	Actual	Estimated[a]	Pearson[c]	Predicted[b]	Pearson[d]
I_{HIGH} (W)	*U*	269 ± 73[A]	290 ± 62[A]	0.87*	261 ± 62	0.99*
	ER	319 ± 50[A]	330 ± 59[A]	0.61*	313 ± 48	0.92*
	EC	451 ± 33[B]	501 ± 83[B, #]	0.45	474 ± 50[#]	0.53
I_{HIGH} (IVO_2max%)	*U*	117 ± 6[A]	129 ± 13[A]	−0.40	114 ± 6	0.62
	ER	124 ± 10[A, B]	129 ± 20[A]	0.46	122 ± 7	0.65*
	EC	130 ± 10[B]	144 ± 20[A, #]	0.15	137 ± 21[#]	0.87*
T_{LOW} (s)	*U*	209 ± 29[A]	159 ± 38[A, #]	−0.40	195 ± 38	0.79*
	ER	170 ± 31[A]	153 ± 50[A]	−0.03	162 ± 42	0.52
	EC	117 ± 29[B]	103 ± 27[B]	−0.16	129 ± 30	0.44

Values are mean ± SD. *U*, $N = 7$; ER, $N = 11$; EC, $N = 13$

Means with the same uppercase superscript were not different only between groups

[a] The TAVO_2max and T_{lim} relationship and CP model were used to generate the estimated values

[b] Predicted values were generated from CP model equation by using the actual values

[c] Correlation coefficients between actual and estimated values

[d] Correlation coefficients between actual and predicted values

[#] Significantly different from actual, $P < 0.05$

* Significant correlation, $P < 0.05$

Discussion

The main finding of this investigation was that the aerobic training status affects the validity of both TAVO_2max and T_{lim} relationship and CP model for estimating I_{HIGH} (W), as the validity becoming progressively lower in individuals with higher aerobic fitness. However, the relationship between the TAVO_2max and T_{lim} was not valid to estimate ET_{LOW}, irrespective of aerobic training status.

Effects of training status

The severe-intensity domain is characterized by the attainment of VO_2max. Several studies have stated that VO_2max is achieved faster at higher intensities (Margaria et al. 1965; Billat et al. 2000; Hill et al. 2002; Hill and Stevens 2005). Indeed, there was a decrease of TAVO_2max, at higher intensities for *U* group. However, for ER and EC there was an intensity effect only between the two extremes, 95 and 110% IVO_2max. It is important to note that at 95% IVO_2max the VO_2 rises slowly towards its maximal value by the occurrence of slow component (Gaesser and Poole 1996; Billat et al. 2000; Ozyener et al. 2001). Despite of mathematical modeling employed in this study do not characterize the different phases of VO_2 kinetics (fast and slow phases), several studies analyzing separately both overall response (MRT) and each phase of VO_2 kinetics showed that the slower overall VO_2 responses were associated with the higher slow components amplitudes (Burnley et al. 2000; MacDonald et al. 1997). Hence, the slower overall VO_2 response at 95% IVO_2max might be responsible for the differences found on TAVO_2max between 95 and 110% IVO_2max. Moreover, the slow component seems to be reduced by aerobic training (Casaburi et al. 1987; Russell et al. 2002; Ocel et al. 2003), which might also provide an explanation for the difference found between 95 and 100% IVO_2max that was only apparent for *U*. Thus, our data confirms that in the severe-intensity domain, TAVO_2max is reduced at higher intensities irrespective of the specificity of training. Additionally, it seems that these differences are attenuated by an increase in aerobic fitness level.

To our knowledge, this study is the first to determine directly the lowest exercise duration and the highest constant exercise intensity at which the VO_2max can still be reached during cycling. EC showed higher I_{HIGH} (451 W) and lower T_{LOW} (117 s) compared to ER (319 W and 170 s) and *U* (269 W and 209 s), and both I_{HIGH} and T_{LOW} were not different between ER and *U* (Table 2). However, differences were not found between EC (130%) and ER (124%) for relative I_{HIGH} (expressed as a percentage of IVO_2max). At other intensities (95, 100 and 110% IVO_2max), there was an effect of specific aerobic training on VO_2 kinetics (TAVO_2max), which also decreased T_{LOW} for a similar I_{HIGH} (IVO_2max%) between EC and ER. Furthermore, for ER the transfer of training effects seems to disappear during high-intensity exercise, as observed for TAVO_2max, I_{HIGH} and T_{LOW}. Thus, adjustments induced by specific aerobic training seem to be required to the best interplay between caption, delivery and O_2 utilization allowing VO_2max be attained quickly, in just ~2 min of

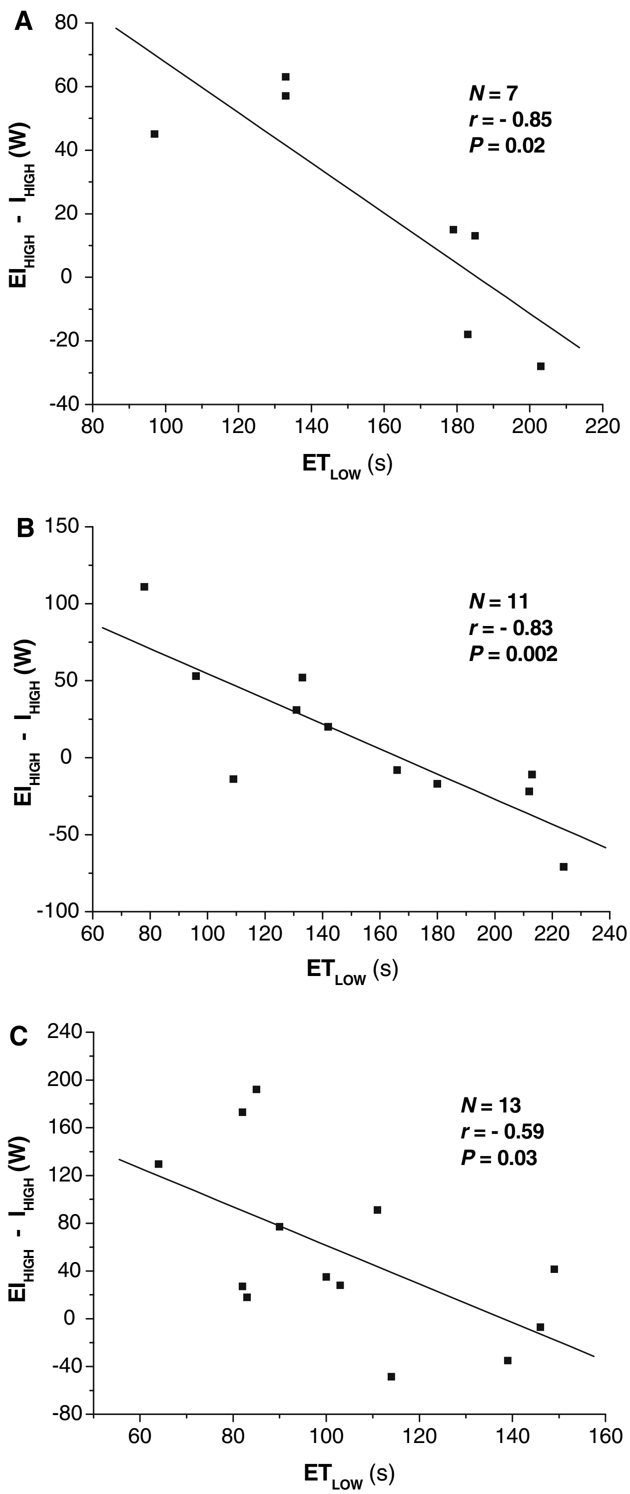

Fig. 5 Relationships between ET_{LOW} and the difference between EI_{HIGH} and I_{HIGH} (bias) for *U* (**a**), for ER (**b**), and for EC (**c**). *Solid line* represents the regression equation

commencement of exercise. Resolution of the determinants of exercise tolerance and their relationships to the VO_2max is of great importance for high-intensity aerobic training elaboration, in order to further increase the aerobic energy release mainly in highly trained athletes, likely sparing anaerobic substrates and prolonging exercise tolerance (Laursen and Jenkins 2002). Future research could to test the applicability and effectiveness of I_{HIGH} and T_{LOW} for prescribing high-intensity aerobic training.

Validity of the proposed models

The main aim of our study was to assess the validity of the ET_{LOW} and EI_{HIGH} estimates from the linear relationship between TAVO_2max and T_{lim} and from the CP model, concerning the aerobic training status. T_{LOW} was higher than ET_{LOW} only for *U* and no significant correlations between each other were observed for all groups. A possible limitation could be the reproducibility of T_{lim} at high-intensity exercise, which might lead to the differences found between T_{LOW} and ET_{LOW}. However, some studies have reported that T_{lim} is highly repeatable, with a difference of no more than 5% between trials performed within severe-intensity domain (Bishop and Jenkins 1995; Carter et al. 2006). This value is less than the 25% difference we have found between T_{LOW} and ET_{LOW} for *U*.

For EC, I_{HIGH} was overestimated by EI_{HIGH}. For *U* and ER, I_{HIGH} was not different and significantly correlated with EI_{HIGH}. In spite of the good correlation showed by *U*, EI_{HIGH} could not be determined in three subjects due to: (1) large differences between TAVO_2max values that increased the slope of linear regression, therefore, the line of regression could not cross the line of identify, or it crossed at an unphysiologically possible value; and (2) the TAVO_2max value projected by monoexponential fit was higher than T_{lim}. The impossibility to estimate EI_{HIGH} in 30% of subjects for *U* group weakens the model proposed by Hill et al. (2002) specifically for this group. Taken together, these results suggest that aerobic training status affects the validity of the proposed models for estimating both ET_{LOW} and EI_{HIGH}, as the validity becoming lower with the increase of the aerobic fitness level.

Possible limitations of the relationship between TAVO_2max and T_{lim}

Analyzing the predictive model utilized to estimate ET_{LOW} we could notice a training effect on the slope of linear regression between TAVO_2max and T_{lim} that resulted in lower ET_{LOW} values compared to T_{LOW} for *U* (Fig. 4). As stated above, this probably occurred in this group of lower aerobic fitness due to the higher effect of slow component (Casaburi et al. 1987; Russell et al. 2002; Ocel et al. 2003) and/or a lower T_{lim} at 95% IVO_2max. Some differences between actual and estimated variables may also be derived from model assumptions that are not fully convincing.

The first assumption is that TAVO_2max decreases linearly at higher intensities until it approaches T_{lim}. This is based upon the strength of the relationship between TAVO_2max and T_{lim}. Indeed, this relationship does not appear to be strong, with a mean correlation of 0.84 between the variables in our study. Furthermore, it is worth noting that TAVO_2max presented by both ER and *U* at 110% IVO_2max were already lower than T_{LOW}. This adds even more disadvantage in using mathematical modeling to indirectly determine T_{LOW}. In this way, the precision of ET_{LOW} was also dependent upon the precision of the determination of TAVO_2max. As TAVO_2max was defined based on VO_2 kinetics (i.e., 4.6 × τ), one possible source of error was the use of a mono-exponential model to fit VO_2 response during exercise at 95% IVO_2max, with the likely emergence of a slow component during the VO_2 response (Gaesser and Poole 1996; Ozyener et al. 2001). Because the present study sought simply to determine TAVO_2max (by overall VO_2 response) and not to characterize the nature of the response, the use of this model seems appropriate (Fig. 2). Nonetheless, since the estimate of τ is associated with an error term, each value of TAVO_2max also has an associated error term. Despite we have performed only one transition, the signal to noise ratio of data can be improved in higher VO_2 amplitudes (Lamarra et al. 1987), therefore, the higher VO_2 amplitude the smaller the confidence interval. In summary, some of these aspects can help to explain the lack of validity of the relationship between TAVO_2max and T_{lim} for estimating ET_{LOW}.

Possible limitations of the CP model

Some authors have indicated the limitation of the two-parameter CP model for estimating the intensity or T_{lim} at high-intensity exercises (Hopkins et al. 1989; Morton 1996; Bosquet et al. 2006). Recently, Bosquet et al. (2006) have shown that critical velocity determined by two-parameter hyperbolic model overestimated the real performance for the exercise duration of ~136 s. In the same way, in the present study the CP model overestimated both the estimated I_{HIGH} (EI_{HIGH}) and predicted I_{HIGH} only for EC, presumably because the effect of reduced exercise duration on the estimates from CP model (Table 2; Fig. 6). For *U* and ER, the CP model estimated and predicted similar intensities for these variables. As expected, the similar value of ET_{LOW} (compared to T_{LOW}) in ER group, when inserted in the CP model, generated similar values between I_{HIGH} and EI_{HIGH}. Unexpectedly, the lower ET_{LOW} for *U* also generated similar values between I_{HIGH} and EI_{HIGH}, even with the CP model not overestimating the

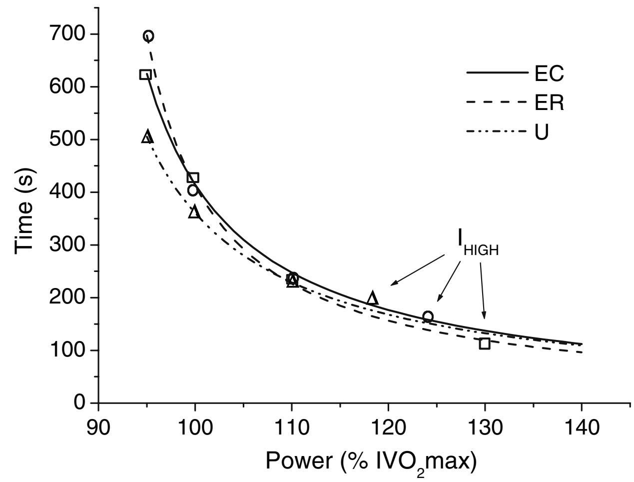

Fig. 6 Representation demonstrating the potential limitation of the two-parameter hyperbolic CP model for estimating the intensity for short exercise duration. Note I_{HIGH} lie outside of regressions lines as decreasing of exercise duration. The *solid*, the *dashed*, and the *dashed dotted lines* represent the regression equations from CP model (using only 95, 100, 110% IVO_2max as predictive trials) for EC, ER, and *U*, respectively. *Open triangle* represents *U*, *open circle* represents ER, *open square* represents EC. See text for details

intensity predicted from T_{LOW}. This likely occurred due to a lower statistical power (type 2 error) as a result of small sample size and large coefficient of variation. Other aspect would be the factual limitation of the CP model for estimating the intensity for short exercise duration, as demonstrated by Bosquet et al. (2006) and in the present study by EC (Fig. 6). Despite this, the CP model did not overestimate EI_{HIGH} for *U* and ER, but we found high significant negative correlations between the bias (EI_{HIGH} − I_{HIGH}) and ET_{LOW} (Fig. 5), suggesting that the shorter the estimated time (ET_{LOW}), the more the CP model overestimated the intensity (EI_{HIGH}).

Possible limitations of the criterion for I_{HIGH} determination

For the determination of I_{HIGH} we assumed that a subject had reached VO_2max when VO_2 was equal or higher than VO_2max (averaging the highest VO_2 values from incremental and constant work rate tests) minus one TEM. Several studies have shown VO_2max is reached at these intensities or similar duration in both running (Billat et al. 2000; Hill et al. 1997; Carter et al. 2006) and cycling (Hill et al. 2002; Caputo and Denadai 2004; Hill and Stevens 2005). This criterion was utilized for two reasons: (1) to individualize the day-to-day biological variability on VO_2max values; (2) not to assume fixed values or fixed percentages of only one test, such as VO_2max obtained in incremental test (VO_2max_{INC}) minus 2.1 ml kg^{-1} min^{-1}

(Billat et al. 1999), or 95% of VO_2max_{INC} (Billat et al. 2000). The utilization of only one value of VO_2max (e.g., VO_2max_{INC}) minus a fixed value can only add to biological variability when used as a reference value for testing on different days, hence it will not be able "to offset" biological variation effect. In order to minimize this effect, it was utilized for each subject the mean of four VO_2max values subtracted by its biological variability (i.e., one TEM). Therefore, our criterion seemed to obtain a more robust and individualized VO_2max, increasing the accuracy of determining I_{HIGH} and T_{LOW} using only one transition. Nevertheless, other experimental designs could obtain a high precision to determine I_{HIGH} and T_{LOW} from averaging repeated bouts.

In conclusion, the present study has shown that the aerobic training status affects the validity of the proposed models for estimating both T_{LOW} and I_{HIGH}. The relationship between the TAVO_2max and T_{lim} was not valid to estimate ET_{LOW}, irrespective of aerobic training status. This relationship appeared to be affected mainly by the slower VO_2 response in the individuals with lower aerobic fitness, which resulted in the lower estimated ET_{LOW}. The exercise intensity estimated from CP model seems to be dependent on exercise duration, suggesting that the model is indirectly affected by aerobic status, since actual and estimated T_{LOW} are reduced via an increase in aerobic fitness. For participants in the present study, depending on the aerobic fitness, the highest intensity and the shortest duration that would permit attainment of VO_2max were, respectively, 117–129% IVO_2max and ~2–3.5 min, on average. These variables might be interesting to prescribe high-intensity interval training, mainly in high trained athletes.

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