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Time Spent Near Maximal Oxygen Uptake During Exercise at Different Regions of the Severe-Intensity Domain

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Abstract

Faricier, R, Fleitas-Paniagua, PR, Iannetta, D, Millet, GY, Keir, DA, and Murias, JM. Time spent near maximal oxygen uptake during exercise at different regions of the severe-intensity domain. *J Strength Cond Res* XX(X): 000–000, 2024—This study applied the critical power (CP) model and several bouts of constant-power exercise within different regions of the severe-intensity domain to determine whether there exists an optimal intensity to maximize time spent near $\dot{V}O_2$peak. Subjects visited the laboratory 9 times. After a ramp-incremental test to determine $\dot{V}O_2$peak and peak power output (PO_{peak}), 9 active individuals (5 females) performed 4 constant-power bouts to task failure between 65 and 100%PO_{peak} to estimate CP and total finite work above CP (W′). Subjects then completed 4 additional exhaustive trials predicted to result in task failure in ~3, 6, 9, and 12 minutes. Time spent at $\dot{V}O_2$peak was calculated as the duration at which $\dot{V}O_2 \geq 95\%$ of the trial-specific $\dot{V}O_2$peak. The level of significance set for the study was $p < 0.05$. Mean CP and W′ were 201 ± 48 W and 17.6 ± 8.4 kJ, respectively. For each bout, time to task failure was 2.7 ± 0.5, 6.3 ± 0.6, 9.5 ± 1.2, and 13.1 ± 3.1 minutes for the 3-, 6-, 9-, and 12-minute conditions. Time spent at $\dot{V}O_2$peak during the 3-minute trial (45 ± 22 seconds) was shorter than during the 9-minute (204 ± 104 seconds; $p = 0.002$) and 12-minute trials (260 ± 155 seconds; $p < 0.001$). The 6-minute trial (117 ± 46 seconds) had shorter ($p = 0.005$) time spent at $\dot{V}O_2$peak compared with the 12-minute trial. At least when performing single bouts of exercise, intensities closer to CP (i.e., those sustainable for ~9 minutes or longer) seem preferable compared with POs in the upper regions of the severe-intensity domain to maximize time at $\dot{V}O_2$peak.

Key Words: critical power, exercise prescription, exercise tolerance, endurance performance

Introduction

Exercise training within the severe-intensity domain (i.e., above the maximal metabolic steady state) at work rates that elicit peak oxygen uptake ($\dot{V}O_2$peak) is an effective strategy to optimize improvements in aerobic fitness (48). This training method has been shown to offer superior gains compared with lower intensities that elicit submaximal $\dot{V}O_2$ (4,11,43), particularly in endurance trained athletes (41).

It has been argued that the benefit of this type of severe-intensity exercise training depends more on the duration spent at $\dot{V}O_2$peak during the training session rather than just the achievement of $\dot{V}O_2$peak per se (11). For example, in recreational cyclists, Turnes et al. (53) compared 2 work-matched interval training programs with work intervals performed in either the upper or lower regions of the severe-intensity domain. Compared with the group that performed lower severe-intensity intervals, the upper severe exercise-intensity training group achieved greater gains in $\dot{V}O_2$peak. This was attributed to longer time spent at $\dot{V}O_2$peak (53). Of note, it has been shown that exercising slightly above the maximal metabolic steady state might not always results in achievement of $\dot{V}O_2$max (19,25). Although the time accumulated near $\dot{V}O_2$peak in training practice is considered important for aerobic adaptions, how far above the maximal metabolic steady state one needs to exercise to maximize the time spent at $\dot{V}O_2$peak during a single exercise bout remains unknown.

In cycling, past findings have shown large variability in individual responses to endurance exercise training between exercise intensity and time spent at $\dot{V}O_2$peak within the severe-intensity domain (20,22,40). For example, when exercising at 100 and 110% of peak power output (PO_{peak}), Hill et al. (20) reported mean time spent at $\dot{V}O_2$peak of 216 ± 74 seconds and 170 ± 38 seconds, respectively, whereas Leclair et al. (40) measured durations at $\dot{V}O_2$peak that were almost half at similar percentages of PO_{peak} (137 ± 63 seconds and 83 ± 38 seconds, respectively). During running, it has been shown that exercising at 100% of the minimal velocity that elicits $\dot{V}O_2$peak during an incremental exercise test elicits the longest time at $\dot{V}O_2$peak (6,7). Such variability in duration at $\dot{V}O_2$peak is highly affected by the methodology used to estimate the bout of exercise. For example, during cycling, the observed differences in duration may stem from the prescriptive approaches used to determine constant-PO exercise and methods of quantifying the time spent at $\dot{V}O_2$peak. For instance, the PO_{peak} is a task-specific outcome that largely depends on the characteristics of the test from which it is measured (i.e., the ramp slope or amplitude and duration of the steps)

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(9,24). Within the same individual, different protocols result in markedly different PO_{peak} even though $\dot{V}O_2$peak is unchanged (24,33,51,54). Thus, the selection of severe-intensity trials based on $\%PO_{peak}$ will result in unpredictable times spent at $\dot{V}O_2$peak because the position of the PO relative to maximal metabolic steady-state is unknown (26,28,44). In contrast to using PO_{peak} for exercise prescription, the critical power (CP)—an estimate of maximal metabolic steady state—provides a superior precision to prescribe severe-intensity domain exercise and its tolerance time. This is because the CP model is based on the hyperbolic power-duration relationship that characterizes exercise performance within the severe intensity domain where the curve asymptote corresponds to CP and the area under that curve at any given time represents the finite amount of work capacity above CP (W′) (18,27,46). This CP model implies that when exercising above CP, exercise duration corresponds to the time at which W′ is fully spent, which depends on the distance between CP and the selected PO (46). Therefore, application of the CP model should diminish interindividual variability to help identify the exercise duration that maximizes the time spent at $\dot{V}O_2$peak within the severe intensity domain.

Only a few study has used CP to characterize the time spent at $\dot{V}O_2$peak within the severe-intensity domain (8,22,38). It was found that severe-intensity exercise that could be tolerated for longer resulted in longer durations spent at $\dot{V}O_2$peak. However, only relatively short exercise durations were evaluated (3, 5, and 7 minutes). It is well established that exercise tolerance within the severe-intensity domain (particularly in its lower regions) can be sustained for up to 20 minutes or longer (10,40,47). Therefore, an incomplete picture remains regarding how the time spent at $\dot{V}O_2$peak changes within the severe-intensity domain and whether there is a relative severe-intensity domain prescription to maximize duration at $\dot{V}O_2$peak. Applying the CP model, this study quantified time spent at $\dot{V}O_2$peak of 4 severe-intensity POs estimated to elicit exercise tolerance times of 3, 6, 9, and 12 minutes. We hypothesized that the lower severe-intensity bouts would elicit the longest time spent at $\dot{V}O_2$peak.

Methods

Experimental Approach to the Problem

This study included 9 visits (Figure 1) performed on an electromagnetically braked cycle ergometer (Velotron; Racer-Mate, Seattle, WA) in a climate-controlled environment at the same time of day (±1 hour). The visits were conducted on separate days (at least 48 h apart) as follows: (a) 1 ramp incremental test performed until task failure to identify maximal responses to exercise, such as $\dot{V}O_2$peak and PO_{peak}; (b) 4 time-to-task failure trials at constant PO between 65 and 100% PO_{peak}; and (c) 4 additional time-to-task failure trials with predicted end-exercise times of 3, 6, 9, and 12 minutes, based on the CP model parameters (CP and W′) derived from the 4 previous % PO_{peak}-based time-to-task failure trials. In this study, task failure was determined as disengagement from the task because of the subject's voluntary exhaustion or a drop by more than 10 rpm for longer than 5 sec from the self-selected optimal cadence despite strong verbal encouragement. For (b) and (c), respectively, the order of the trials was randomized. During each trial, gas exchange, ventilatory, and heart rate responses were continuously measured. Blood lactate concentration ([BLa^-]) samples were collected at task failure. As each trial was performed until exhaustion, all the subjects were vigorously and consistently encouraged to provide a maximal effort. In addition, the subjects were encouraged to rest and advised to avoid strenuous or unfamiliar activities within the 24 hours before testing and to restrain from caffeine or energy drinks for 2 hours and take their last meal 2 hours before the testing session.

Subjects

Nine healthy recreationally active individuals (5 females) volunteered to participate in the study. Subjects' characteristics were 25 ± 5 years old (range: 20–36 years old), 1.73 ± 0.07 m, 73.1 ± 13.9 kg, and 24.3 ± 3.6 $kg \cdot m^{-2}$ for the age, height, body mass, and body mass index, respectively. This population has been selected as it has been reported that, in healthy individuals, the CP parameters were relatively consistent when estimated over consecutive weeks (52). Prescreening questionnaires were used to determine the eligibility and to guarantee that subjects did not present any symptoms of respiratory, cardiovascular, or metabolic disease or musculotendinous injury. A consent form containing a detailed description of the study protocol and associated risks and benefits was presented to each subject. All subjects were conscious of their right to withdraw at any time from the study and gave written informed consent. The study procedures were approved by the Conjoint Health Research Ethics Board of the University of Calgary and respected the Declaration of Helsinki.

Experimental Procedures

On visit 1, the subjects performed a ramp-incremental test to determine their $\dot{V}O_2$peak and PO_{peak}. The ramp-incremental trial began with 4 minutes of baseline cycling at 20 W, followed by a 6-minute square wave transition within the moderate domain at PO of 60–100 W, according to sex, body, and training status. Then, the PO was immediately dropped down to the 20 W baseline for 4 minutes, after which the ramp test started at a rate of 30 $W \cdot min^{-1}$ until task failure. A blood sample was taken at the end of the ramp test to measure peak [BLa^-].

Then, on separate days, subjects performed 4 constant PO trials to task failure to determine the CP and W′ parameters. Each trial began with a standardized 4-minute baseline at 20 W before an immediate increase to the targeted PO. For optimal distribution of times at task failure (TTF), a first trial was performed at $80\%PO_{peak}$, and then the intensity was increased or reduced based on the TTF. The same approach was used to determine the intensity of the following trials. The TTF of the 4 trials aimed to last between 2 and 15 minutes as recommended elsewhere (27,46) (Table 2). Subjects were asked to self-determine their optimal cadence during the first time-to-task failure trial and to pedal at this rate for all successive trials. The TTF was measured to the nearest second using a standard chronometer, and [BLa^-] was measured immediately after task failure.

After determining their CP and W′ parameters, each subject performed 4 additional time-to-task failure trials that were expected to last 3, 6, 9, and 12 minutes. The PO to elicit each of these time-predicted trials was determined based on individuals' CP and W′ parameters as follows:

$$PO = CP + (W' / Time)$$

with PO being expressed in W and Time in seconds. During these trials, only the subjects were blinded from the expected

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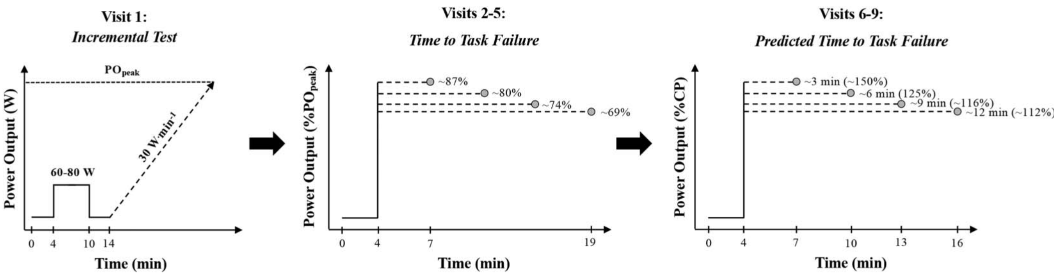

Figure 1. Schematic representation of the study experimental protocol.

time at task failure. Each time-predicted trial was performed under similar conditions as previously mentioned, and a [BLa^-] sample was also taken after task failure.

Equipment and Data Collection. Gas exchange and ventilatory variables were measured using a mixing chamber linked to a metabolic cart (Quark CPET; Cosmed, Rome, Italy). Data were averaged and recorded every 10 seconds. During each trial, subjects were equipped with a face mask attached to a 2-way nonrebreathing valve connected to the mixing chamber via a 1-meter hose to allow expired gases to collect in the mixing chamber. Flow rate and fractional gas concentrations were recorded using a low dead-space turbine and a gas sampling line directly connected to the mixing chamber, respectively. Before each test, the metabolic cart was calibrated following manufacturer recommendations. The metabolic cart was switched on for at least 30 minutes before the beginning of the calibration. Then, the gas analyzer was calibrated with a known gas concentration mixture (16% O_2, 5% CO_2, and balance N_2). The turbine was calibrated for inspired and expired air flows and volumes using a 3-L syringe. The [BLa^-] was measured with a blood lactate analyzer (EKF Biosen C-Line; EKF Diagnostics, Barleben, Germany). After collecting 20 μL of blood in a specific capillary tube, the blood sample was diluted and mixed in a prefilled plastic bottle containing a substance for this purpose.

Data Analysis. Before each analysis, $\dot{V}O_2$ versus time data were fitted using a linear model (ramp-incremental test) or monoexponential model (time-predicted trials) (Origin software, Origin Lab, Northampton, MA). The $\dot{V}O_2$ data points laying ± 3 *SD*s from the local mean were removed. Then, $\dot{V}O_2$ data were interpolated to second-by-second and used for analysis.

During the ramp test, the $\dot{V}O_2$peak was determined as the highest 10-second average value. The PO_{peak} corresponded to PO reached at task failure.

The CP and W′ parameters were estimated using a free online app (https://www.exphyslab.com/cp, *ExPhysLab*). The time (in seconds) and PO (in W) were uploaded to the software where 3 different two-parameter fitting models were computed.

1. 1. Two-parameter, hyperbolic PO–TTF model:

$$TTF = W' / (PO—CP)$$

1. 2. Two-parameter, linear work–TTF model

$$W = (CP \times TTF) + W'$$

1. 3. Two-parameter, linear PO–1/TTF model

$$PO = W' \times (1/TTF) + CP$$

For each subject, the model with the lowest sum of standard errors (*SEE*) for CP and W′ was identified as the best-fit model. This model was accepted based on recent evidence that indicated that these estimations generated POs that were not different from the PO associated to the maximal metabolic steady state (27). However, we do not propose that this model is the gold-standard that should be considered for CP and W′ determination as it is known that different approaches might elicit somewhat different results (2,12,17,42). Then, the CP and W′ parameters derived from this best-fit model were used to calculate the PO for each time-predicted trial.

The intraindividual fluctuations in $\dot{V}O_2$peak estimated to be ~5.6% (ranging from 3.8 to 8.3%) in healthy individuals were accounted for in the analysis (32). Given this variability, $\dot{V}O_2$peak was defined test-by-test as the highest 10-second average $\dot{V}O_2$ during each trial, and an error of ±5% of this bout-specific value was used to compute the time spent at $\dot{V}O_2$peak as previously recommended (15). Thus, the time spent at $\dot{V}O_2$peak was calculated as the total time that $\dot{V}O_2$ exceeded 95% of the bout specific $\dot{V}O_2$peak for each trial.

Statistical Analyses

Data are presented as mean ± *SD*. The normality of the data was verified using Shapiro-Wilk's test. Repeated measures ANOVAs were used to investigate whether there was a condition effect for $\dot{V}O_2$peak, time to reach 95% of the daily $\dot{V}O_2$peak, the time spent at $\dot{V}O_2$peak¸ [BLa^-], and RPE. Sphericity was verified using Mauchly's Test. If the homogeneity of the variances assumptions was violated, the Greenhouse-Geisser's correction was applied. Bonferroni's *post hoc* tests were used to establish where the difference(s) occurred. The significance level was set at a *p*-value lower than 0.05.

Results

Table 1 lists the characteristics of each subject and the peak values achieved during the ramp-incremental protocol. At task failure, RPE was 9.0 ± 0.7. The responses for each of the time to task failure trials used to derive CP and W′ are presented in Table 2, organized from the shortest (Trial 1) to the longest (Trial 4). Power-time series modeling of these data provided a mean CP and W′ of 201 ± 48 W and 17.6 ± 8.4 kJ, respectively, with *SEE* of 1.9 ± 0.9% and 8.1 ± 3.2%.

The responses for each time-predicted trial are presented in Table 3. The mean PO for the time-predicted trials aimed to last 3,

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Table 1

Individual's standard ramp-incremental exercise and critical power performance measurements.*

Subjects #—Sex	PO W	$\dot{V}O_2$max $L \cdot min^{-1}$	$\dot{V}O_2$max $mL \cdot kg^{-1} \cdot min^{-1}$	[Bla⁻] $mmol \cdot L^{-1}$	CP %POpeak
1—F	265	2.71	40.3	10.4	61
2—M	425	4.89	55.5	9.9	66
3—F	285	3.13	49.4	11.2	61
4—M	405	4.34	56.3	12.5	67
5—F	315	3.57	55.2	9.2	71
6—M	312	3.81	37.9	10.9	54
7—F	255	2.63	44.5	11.8	59
8—F	337	3.64	58.9	12.0	63
9—M	284	3.08	40.4	7.6	58
Mean	320	3.53	48.7	10.6	62
SD	60	0.75	8.1	1.5	5
CV	19%	21%	17%	15%	8%

*[BLa⁻] = blood lactate concentration measured immediately after task failure; CP = critical power; CV = coefficient of variation; PO_{peak} = highest power output reached during the ramp-incremental test; $\dot{V}O_{2r}$max = highest oxygen uptake response measured over a 10-s rolling average during the ramp-incremental test.

6, 9, and 12 minutes were 299 ± 79 W, 250 ± 61 W, 234 ± 56 W, and 225 ± 54 W, respectively, which represented 150 ± 25%, 125 ± 12%, 116 ± 8%, and 112 ± 6% of CP. The mean measured TTFs were for the 3-minute trial (2.7 ± 0.5 minutes), the 6-minute trial (6.3 ± 0.6 minutes), the 9-minute trial (9.5 ± 1.2 minutes) or the 12-minute trial (13.1 ± 3.1 minutes). A condition effect was found for the $\dot{V}O_2$peak ($p = 0.009$), where the mean $\dot{V}O_2$peak measured during the 3-minute trial was lower ($p = 0.016$) than the 6-minute trial (Table 3). However, the $\dot{V}O_2$peak measured in each of the trials did not differ from each other or that obtained during the ramp-incremental test ($p = 0.592$ for 3 minutes; $p = 1.000$ for 6 minutes; $p = 1.000$ for 9 minutes; and $p = 1.000$ for 12 minutes), thus confirming the achievement of $\dot{V}O_2$peak.

The mean times to reach $\dot{V}O_2$peak were 114 ± 20 seconds, 232 ± 39 seconds, 333 ± 85 seconds, and 363 ± 148 seconds for the 3-, 6-, 9-, and 12-minute conditions, respectively (Figure 2A). These durations corresponded to 70.2 ± 11.8%, 60.6 ± 13.2%, 57.1 ± 17.2%, and 48.7 ± 15.2% of TTF, respectively (Figure 2B). The absolute time to achieve $\dot{V}O_2$peak after exercise onset was significantly shorter for the 3-minute condition compared with the 6-minute ($p = 0.011$), 9-minute ($p < 0.001$), and 12-minute conditions ($p < 0.001$) and for 6-minute condition compared with the 9-minute ($p = 0.039$) and 12-minute conditions ($p = 0.004$). When expressed relative to the total time to task failure, the time to achieve $\dot{V}O_2$peak after exercise onset was significantly longer for the 3-minute condition compared with the 9-minute ($p = 0.048$) and 12-minute conditions ($p < 0.001$).

The mean time spent at $\dot{V}O_2$peak were 45 ± 22 seconds, 117 ± 46 seconds, 204 ± 104 seconds, and 260 ± 155 seconds for the 3-, 6-, 9-, and 12-minute conditions, respectively (Figure 3A). These durations corresponded to 26.8 ± 11.0%, 30.4 ± 11.5%, 35.4 ± 16.0%, and 32.1 ± 16.5% of TTF, respectively (Figure 3B). Compared with the mean time spent at $\dot{V}O_2$peak in the 3-minute condition, the time spent at $\dot{V}O_2$peak was greater during the 9-minute ($p = 0.002$) and 12-minute ($p < 0.001$) conditions and also greater in the 12-minute condition compared with the 6-minute condition ($p = 0.005$). No significant time effect was found for the time spent at $\dot{V}O_2$peak expressed relative the total time to task failure ($p = 0.393$). The mean coefficient of variation (CV) in $\dot{V}O_2$peak between the ramp-incremental test and the 4 time-predicted trials was 3.9 ± 1.6% (ranging from 2.1 to 6.7%).

At task failure, [BLa⁻] was 9.8 ± 2.2 $mmol \cdot L^{-1}$, 11.5 ± 1.4 $mmol \cdot L^{-1}$, 11.0 ± 1.8 $mmol \cdot L^{-1}$, and 10.1 ± 1.2 $mmol \cdot L^{-1}$ for the 3-, 6-, 9-, and 12-minute conditions, respectively. Further, RPE was 8.2 ± 1.0, 8.7 ± 0.9, 8.4 ± 1.1, and 8.6 ± 1.5 for the 3-, 6-, 9-, and 12-minute conditions, respectively. There was no condition effect between the end-ramp and end-time trials for [BLa⁻] ($p = 0.164$) and RPE ($p = 0.439$).

Discussion

In training practice, high-intensity exercise that elicits $\dot{V}O_2$peak is considered a useful method to maximize enhancements of aerobic performance (4,11). Using the CP model, we compared the time spent at $\dot{V}O_2$peak at 4 different exercise intensities within the severe-intensity domain ranging from ~3 to 12 minutes before task failure in healthy, recreationally active individuals. The key finding was that the time spent at $\dot{V}O_2$peak was longer with increased exercise duration (~9–12 minutes), despite a slower time to achieve $\dot{V}O_2$peak. However, when expressed in proportion to the total exercise duration, the time spent at $\dot{V}O_2$peak was not

Table 2

Individuals' and average results of the time-to-task failure trials (from the shortest [trial 1] to the longest [trial 4]).*

	Trial 1				Trial 2				Trial 3				Trial 4			
Subjects #	PO % PO_{peak}	Time s	$\dot{V}O_2$peak $L \cdot min^{-1}$	[BLa⁻] $mmol \cdot L^{-1}$	PO % PO_{peak}	Time s	$\dot{V}O_2$peak $L \cdot min^{-1}$	[BLa⁻] $mmol \cdot L^{-1}$	PO % PO_{peak}	Time s	$\dot{V}O_2$peak $L \cdot min^{-1}$	[BLa⁻] $mmol \cdot L^{-1}$	PO % PO_{peak}	Time s	$\dot{V}O_2$peak $L \cdot min^{-1}$	[BLa⁻] $mmol \cdot L^{-1}$
1	80	189	2.47	9.9	75	244	2.52	9.8	70	458	2.64	10.7	65	686	2.53	8.8
2	95	229	5.08	13.0	85	319	5.09	11.9	80	522	4.95	13.5	75	645	4.85	11.3
3	90	131	2.84	11.0	80	210	2.96	10.0	70	502	3.05	8.7	65	808	2.73	6.8
4	90	239	4.40	15.7	80	488	4.62	14.7	75	655	4.32	12.1	73	867	4.43	11.6
5	85	227	3.47	13.6	80	339	3.59	11.9	77	493	3.51	12.6	75	805	3.51	12.8
6	93	281	4.03	14.0	90	290	3.93	12.4	80	508	4.06	14.8	70	679	3.72	12.8
7	80	270	2.65	13.8	75	337	2.67	9.4	70	551	2.73	11.3	65	929	2.58	12.0
8	80	244	3.47	11.7	75	378	3.55	10.7	71	476	3.58	12.1	68	908	3.25	12.1
9	87	191	3.07	8.8	80	267	2.84	10.8	70	521	3.22	11.9	64	833	3.27	10.5
Mean	87	222	3.50	12.4	80	319	3.53	11.3	74	521	3.56	12.0	69	796	3.43	11.0
SD	6	46	0.87	2.2	5	82	0.89	1.7	4	57	0.76	1.72	5	103	0.81	2.0
CV	7%	21%	25%	18%	6%	26%	25%	15%	6%	11%	21%	14%	7%	13%	23%	18%

*PO stands for power output and represents the percentage of peak power output (PO_{peak}) derived from the ramp-incremental test. Time indicates the measured time at task failure. $\dot{V}O_2$peak indicates the highest oxygen uptake response measured over a 10-s average period. [BLa⁻] indicates the blood lactate concentration measured immediately after task failure, and CV indicates coefficient of variation.

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Table 3
Individuals' and average results of the 4 time-predicted trials.*

Subjects	3 min					6 min					9 min					12 min				
#	PO %CP	Time s	$\dot{V}O_2$peak L·min^{-1}	t$\dot{V}O_2$peak s	[BLa$^-$] mmol·L^{-1}	PO %CP	Time s	$\dot{V}O_2$peak L·min^{-1}	t$\dot{V}O_2$peak s	[BLa$^-$] mmol·L^{-1}	PO %CP	Time s	$\dot{V}O_2$peak L·min^{-1}	t$\dot{V}O_2$peak s	[BLa$^-$] mmol·L^{-1}	PO %CP	Time s	$\dot{V}O_2$peak L·min^{-1}	t$\dot{V}O_2$peak s	[BLa$^-$] mmol·L^{-1}
1	133%	208	2.65	47	7.3	117%	382	2.77	76	10.7	111%	578	2.76	239	10.5	108%	554	2.55	265	9.6
2	156%	155	4.65	34	10.1	128%	380	5.00	75	13.1	119%	603	4.94	228	13.0	114%	723	4.65	383	10.1
3	135%	197	3.08	57	11.0	117%	362	3.04	116	8.8	112%	565	2.96	208	7.9	109%	844	3.08	247	9.5
4	146%	109	4.16	16	9.1	123%	374	4.68	115	11.6	115%	531	4.91	114	12.5	112%	836	4.58	250	11.5
5	125%	173	3.45	55	9.7	113%	357	3.50	174	12.5	109%	408	3.45	173	12.2	106%	600	3.29	76	10.8
6	209%	160	3.96	24	13.7	154%	384	3.98	113	13.0	136%	621	3.80	154	12.1	127%	1,126	3.73	332	11.8
7	152%	172	2.59	67	11.0	126%	467	2.77	173	11.8	117%	610	2.60	309	8.9	113%	713	2.55	155	9.3
8	137%	174	3.37	82	10.2	118%	381	3.70	161	11.3	112%	661	3.68	384	10.0	109%	1,017	3.42	559	10.4
9	153%	134	2.75	27	6.1	126%	339	3.20	40	10.5	118%	540	3.21	30	11.6	113%	684	3.27	70	8.0
Mean	150%	165	3.41	45	9.8	125%	381	3.63†	116	11.5	116%	569	3.59	204	11.0	112%	789	3.46	260	10.1
SD	25%	30	0.72	22	2.2	12%	36	0.80	47	1.4	8%	73	0.85	104	1.7	6%	188	0.76	155	1.2
CV	26%	18%	21%	48%	23%	10%	9%	22%	41%	12%	7%	13%	24%	51%	16%	5%	24%	22%	60%	12%

*[BLa$^-$] = blood lactate concentration measured immediately after task failure; CP = critical power; CV = coefficient of variation; PO = power output and represents the percentage of CP derived from the ramp-incremental test. Time indicates the measured time at task failure; $\dot{V}O_2$peak = highest oxygen uptake response measured over a 10-second average period. t$\dot{V}O_2$peak = sum of each value above 95% of the daily $\dot{V}O_2$peak.
†Significantly ($p < 0.05$) different from the 3-minute condition.

different between the conditions. This study provides novel information into the relationship between exercise tolerance and time sustained at $\dot{V}O_2$peak during a single bout of cycling exercise within the severe intensity domain. These findings could be used in practice to develop exercise training protocols that aim to maximize the time spent at $\dot{V}O_2$peak.

Constant-intensity exercises that can be sustained for ~9–12 minutes within the severe-intensity domain yielded longer exercise durations at $\dot{V}O_2$peak. This observation is consistent with previous studies that have reported a reduction in the time spent at $\dot{V}O_2$peak at greater %PO_{peak} associated with shorter task durations (1,20,21). Key limitations of this previous work are that exercise at fixed %PO_{peak} does not guarantee severe-intensity exercise within an individual (i.e., exercise could be in the heavy- or extreme-intensity domains) nor do they ensure similar proximity to maximal metabolic steady-state between individuals (i.e., %PO_{peak} at CP will vary from person-to-person), which could have resulted in the inability to achieve $\dot{V}O_2$peak (26). Using a CP-based approach, Hill and Stevens measured times spent at $\dot{V}O_2$peak of 47, 108, and 242 seconds for predicted exercise duration of 3, 5, and 7 minutes, respectively (22). At these shorter durations, time spent at $\dot{V}O_2$peak were comparable with those that we obtained at 3 minutes (45 ± 22 seconds) and 6 minutes (117 ± 46 seconds). Collectively, these findings show that longer severe-intensity exercise training intervals (i.e., those performed closer to CP) increase time spent at $\dot{V}O_2$peak. It should be mentioned that, during running, it has been shown that the duration for which $\dot{V}O_2$peak can be sustained is the longest at the velocity corresponding to 100% of the minimal velocity, which elicits $\dot{V}O_2$peak during an incremental exercise protocol and any exercise intensities greater or lower than that results in a shorter time at $\dot{V}O_2$peak (7). However, in the present study, there were no differences in time spent at $\dot{V}O_2$peak for our 2 longest trials (i.e., those predicted to elicit exhaustion in 9 and 12 minutes). The absence of difference between the 9-minute (204 ± 104 seconds) and 12-minute bouts (260 ± 155 seconds) could be explained by the error associated with CP model predictions particularly for longer durations of exercise. Although all subjects exercised at progressively lower POs from the 3- to 12-minute condition and the average TTFs were not different from the target durations, there was considerable interindividual variability in TTF (CV: ~12 and ~24% for the 9- and 12-minute condition, respectively) such that for the 12-minute condition some exercised nearer to 9 minutes and others nearer to 12 minutes in the 9-minute condition. Nevertheless, the CP model remains a highly reliable method to prescribe severe exercise with a CV ranging from 2.4 to 6.5% (30). In running, it has been shown that interindividual variability in time to exhaustion was explained by the aerobic speed reserve concept, which characterizes the range of velocities between critical velocity and the velocity associated with 100% $\dot{V}O_2$peak, where longer times to exhaustion were measured in individuals exercising at a lower percent of their aerobic speed reserve (8). Nevertheless, as it is the case with PO_{peak}, evidence has shown that the velocity associated with 100% $\dot{V}O_2$peak is a task-specific variable, which limits its transferability to different populations and protocols (3,5,36,49). Although the present data indicate that using CP for predicting TTF adds precision to the exercise prescription, some level of imprecision is an inherent feature of the CP model, which needs to be considered when applying this method for exercise prescription (34). In fact, a recent investigation proposed that using the power-law model may represent a safer tool for exercise intensity selection than the hyperbolic model from which CP is typically derived, as the former

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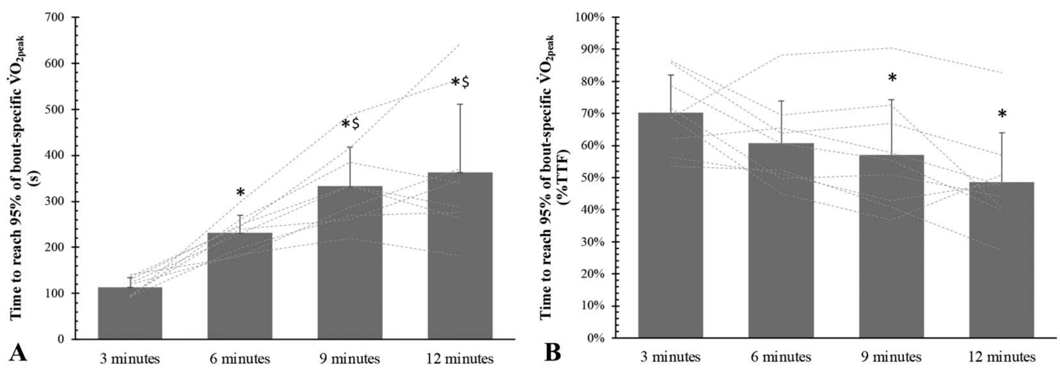

Figure 2. Time to reach 95% of bout-specific $\dot{V}O_2$peak expressed in absolute (panel A) and in proportion to individual time at task failure for each trial (panel B) with expected time at task failure condition (3, 6, 9, and 12 minutes). The bar chart and dashed lines represent the mean and individual results. The symbols "*" and "\$" indicate significantly different from 3-minute and 6-minute expected time at task failure condition ($p < 0.05$), respectively.

more naturally models fatigue than the latter (14). However, the benefits of the power-law model require further investigation.

The time spent at $\dot{V}O_2$peak depends on how fast $\dot{V}O_2$peak is achieved after exercise onset. When exercising at constant-PO within the severe-intensity domain, the $\dot{V}O_2$ response follows an exponential-like profile until plateauing at $\dot{V}O_2$peak (47). In our data, the PO furthest from CP resulted in the quickest achievements of $\dot{V}O_2$peak indicating that the rate of adjustment in $\dot{V}O_2$ is faster in the upper regions of the severe-intensity domain (Figure 4). This is in line with previous studies of supra-CP $\dot{V}O_2$ kinetics (45). However, our data also demonstrated that the longest time at $\dot{V}O_2$peak were measured during the longest exercise trials. This might be explained by the fact that $\dot{V}O_2$peak achievement occurred at lower %TTF. We measured that $\dot{V}O_2$peak was achieved after 57 and 49% TTF for the ~9- and ~12-minute conditions while only after 70% for the 3-minute condition. A lower %TTF is associated with a lower W′ depletion at which $\dot{V}O_2$peak achievement occurs, which thus extends the time for which the $\dot{V}O_2$peak can be sustained. This result reinforces the notion that longer constant-intensity exercises must be preferred in the severe domain to maximize the time spent at $\dot{V}O_2$peak.

In practice, exercise intensities located within the lower region of the severe-exercise intensity domain should be preferred to maximize the time spent at $\dot{V}O_2$peak. Near CP, even a single bout of exercise that can be tolerated for ~9–12 minutes could accumulate ~3–5 minutes at $\dot{V}O_2$peak. By contrast, 4 bouts of exercise that can be tolerated for ~3 minutes would need to be completed until task failure to accumulate only 3 minutes at $\dot{V}O_2$peak. Thus, considering the recovery time between bouts of exercise, ~50% more total time would be needed for the workout to still spend less time at $\dot{V}O_2$peak. In addition, for interval exercise training protocols that aim to achieve $\dot{V}O_2$peak at each repetition, 60% TTF at the velocity corresponding 100% of $\dot{V}O_2$peak has been considered as the optimal interval duration to design interval training (39). However, our results demonstrated that the %TTF at which $\dot{V}O_2$peak is achieved varied with exercise durations within the severe-exercise intensity domain. On average, $\dot{V}O_2$peak was achieved at ~50–60% TTF for exercise intensity that are closest to CP and that can be tolerated for ~9–12 minutes, but 70% TTF for exercise intensities in the upper region of the severe-exercise intensity domain that can be tolerated for less than ~3 minutes. However, for all conditions, we measured a large interindividual variability in the times at which $\dot{V}O_2$peak was achieved and sustained, which should be considered when trying to assign a fixed duration to the exercise bout. Although the small sample size limited the statistical power necessary to draw reliable conclusions, we explored how sex and training differences could have impacted the findings. On average, females seemed to exhibit a longer time near $\dot{V}O_2$peak than males for a given CP-predicted exercise duration within the severe intensity domain, possibly because of faster achievement of their $\dot{V}O_2$peak, as seen in the present data set. However, future studies should

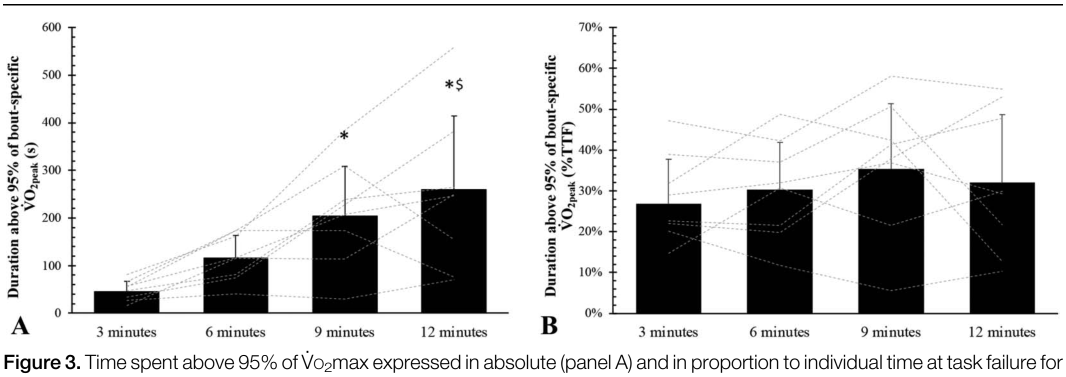

Figure 3. Time spent above 95% of $\dot{V}O_2$max expressed in absolute (panel A) and in proportion to individual time at task failure for each trial (panel B) with expected time at task failure condition (3, 6, 9, and 12 minutes). The bar chart and dashed lines represent the mean and individual results. The symbols "*" and "\$" indicate significantly different from 3-minute and 6-minute expected time at task failure condition ($p < 0.05$), respectively.

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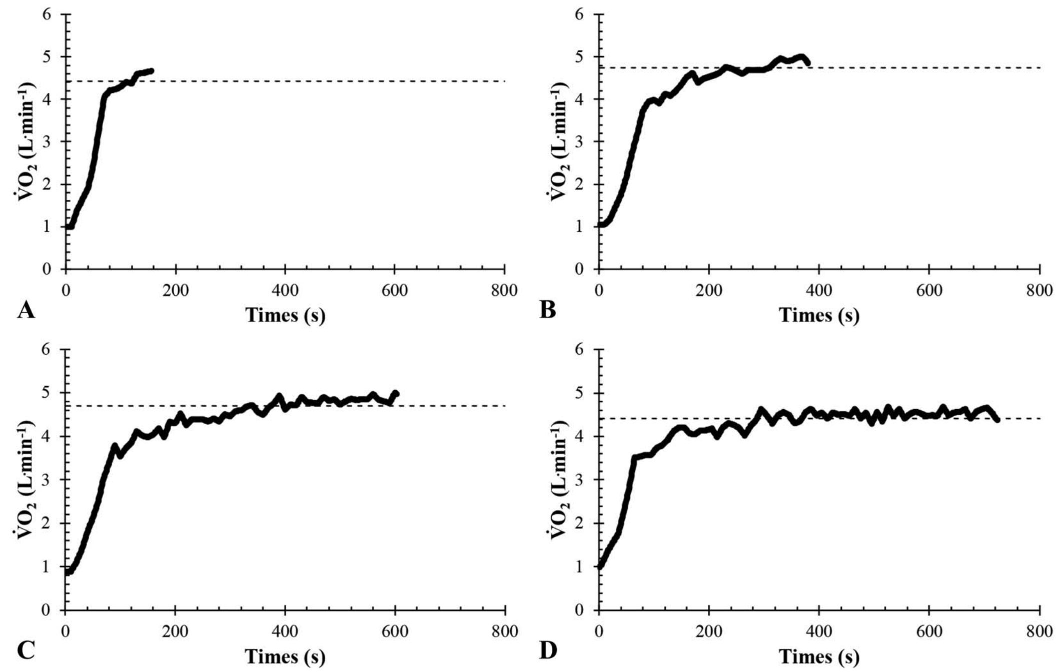

Figure 4. Time course of $\dot{V}O_2$ responses during the 4 time-predicted trials of a representative subject. The results of the 3-, 6-, 9-, and 12-minute conditions are presented in panels A, B, C, and D, respectively. The horizontal dashed lines represent the daily $\dot{V}O_2$peak. Time spent above $\dot{V}O_2$max was computed for each condition as the cumulative duration during which $\dot{V}O_2$ was ≥95% of the bout-specific $\dot{V}O_2$peak.

adequately address this question to determine whether this trend was merely coincidental or potentially real, and what factors might contribute to this occurrence. Regarding training status, it is well established that endurance athletes exhibit different faster $\dot{V}O_2$ kinetics and larger $\dot{V}O_2$peak values compared with untrained individuals (35,36). However, no significant correlations between $\dot{V}O_2$peak and time to reach $\dot{V}O_2$peak were found, which may be explained by the relatively homogenous fitness level in this study (range: 37.9 to 58.9 ml^{-1}·kg^{-1}·min, with most subjects close to 50 ml^{-1}·kg^{-1}·min). Therefore, our findings specifically apply to individuals with characteristics similar to those of the population we studied, namely healthy, recreationally active individuals. Indeed, findings may differ in populations with clinical conditions impacting exercise tolerance and/or $\dot{V}O_2$ kinetics and in highly trained athletes.

From methodological consideration, it is important to note that, although known as a valid approach to establish the boundary separating heavy from severe intensity exercise, the determination of CP based on multiple trials may be unpractical and significant differences in the CP parameter estimates may exists according to the mathematical model used (2,12,17). Recently, Jones et al. (31) recommended using the best individual fit model, which results in the least mean cumulated error for CP and W′, which we used for the present study. Nevertheless, changes in the CP and W′ estimations between models would have been very small independently of the selected approach: 197 ± 48 W and 19.6 ± 8.9 kJ for the two-parameter, hyperbolic PO–TTF model (mean total error: 15 ± 8%); 200 ± 49 W and 18.2 ± 8.4 kJ for the two-parameter, linear work–TTF model (mean total error: 13 ± 6%); and 201 ± 48 W and 17.6 ± 8.5 kJ for the two-parameter, linear PO–1/TTF model (mean total error: 11 ± 4%) versus 201 ± 48 W and 17.6 ± 8. kJ for the "best-fit" model (mean total error: 10 ± 4%). Compared with the standard multiple trial-based CP model, it has been recently demonstrated that the CP parameters (CP and W′) can be directly estimated from a single visit step-ramp-step protocol (29).

Another aspect to consider is that in this study, we accepted a biological variability in $\dot{V}O_2$peak of 5% based on Katch and et al. who reported a day-to-day fluctuation in $\dot{V}O_2$peak of ~5.6% (ranging from 3.8 to 8.3%) in healthy individuals (32). However, a recent study has indicated that this variability could be of ~2.8% (55). If we were to calculate the responses based on that variability, then (a) the time spent at $\dot{V}O_2$peak would be reduced to 32, 71, 100, and 113 seconds for 3, 6, 9, and 12 minutes, respectively, compared with 5% and (b) between time-predicted condition, the time spent at $\dot{V}O_2$peak would only be significantly lower in the 3-minute condition compared with the 9-minute condition.

Important to consider is also that, although the use of a $\dot{V}O_2$peak approach (i.e., ≥95% of ramp $\dot{V}O_2$peak) might lead to slightly different results, time spent at $\dot{V}O_2$peak was computed as the duration during which $\dot{V}O_2$ was ≥95% of the bout-specific $\dot{V}O_2$peak, as recommended elsewhere (15). Although the mean $\dot{V}O_2$peak responses were not different between the ramp-incremental exercise and all-time conditions, it is possible that some subjects may not have achieved their "true" $\dot{V}O_2$peak during the 3- and 12-minute conditions (2,27,50). The PO partitioning severe-from extreme-intensity domains (i.e., where the PO is so high that $\dot{V}O_2$ kinetics do not have time to attain $\dot{V}O_2$peak before task failure ensues) is often associated with tolerable durations approximating between 2 and 3 minutes (20,23). Given that TTF in 2 subjects was below 2.5 minutes in the 3-minute condition, it is possible that they might have exercised within the extreme-intensity domain. Thus, although the overall response

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during the 3-minute trials indicates that $\dot{V}O_2$peak was achieved, the likelihood of exercising within the severe intensity domain should be considered when aiming for greater intensity and shorter duration bouts that aims to achieve $\dot{V}O_2$peak responses. For instance, no differences were observed in [BLa$^-$] and RPE responses between time-predicted trials (3, 6, 9, and 12 minutes) and the ramp test. This confirms that, on average, the subjects provided consistently a maximal effort for each trial.

We recognize that using "bout-specific" $\dot{V}O_2$peak could be perceived as a limitation according to the magnitude of day-to-day variability accepted. An alternative approach would be to use the $\dot{V}O_2$peak during the ramp-incremental test as the "true $\dot{V}O_2$peak" response during cycling exercise. With this approach, the time spent at $\dot{V}O_2$peak would be changed to 33, 172, 230, and 182 seconds for 3, 6, 9, and 12 minutes, respectively, compared with the use of "bout-specific" $\dot{V}O_2$peak, where the time spent at $\dot{V}O_2$peak would only be significantly lower in the 3-minute condition compared with the 6 and 9-minute conditions between conditions. However, a limitation of this approach is the assumption that $\dot{V}O_2$peak itself does not vary daily (32,55). This is unlikely because of factors such as measurement error, biological variability, and familiarization or practice that can cause $\dot{V}O_2$peak to oscillate from test to test (16). Moreover, if we were to use the ramp incremental test $\dot{V}O_2$peak as the "reference" $\dot{V}O_2$peak and accepted a 5% error range as valid, some subjects would not have spent time at $\dot{V}O_2$peak. In this case, 2 scenarios are possible: (a) that subjects did not actually achieve $\dot{V}O_2$peak during those trials and (b) that selected approach (i.e., using the ramp specific $\dot{V}O_2$peak as the reference value) did not allow to capture the $\dot{V}O_2$peak response. No matter what approach we selected, a certain level of uncertainty would exist. In defense of the adopted approach, only in 4 out of 36 cases, the $\dot{V}O_2$peak during the TTF trials was slightly below the 95% $\dot{V}O_2$peak during the ramp incremental test. This occurred during the 3-minute TTF trials in 2 occasions and during the 12-minute TTF trials in the other 2. Although it is likely that the shorter duration trials might not always allow for the $\dot{V}O_2$peak to be fully developed, this should not be the case during the 12-minute TTF trials. Interesting, during these longer trials, 1 subject reached 93% and the other 1 94% of the ramp specific $\dot{V}O_2$peak. As an example, whereas subject #5 exercised at 93% of the ramp-specific $\dot{V}O_2$peak and lasted for 76 seconds at $\dot{V}O_2$peak, subject #9 exercised at 110% of the ramp-specific $\dot{V}O_2$peak lasted for 70 seconds. Therefore, with our approach, we considered that $\dot{V}O_2$peak could have changed between tests, and we accepted that this variability could be slightly greater than the previously discussed 5% in 4 out of 36 trials. This is in line with the work of Dupont and et al., who aimed to find a reliable method for quantifying time spent at $\dot{V}O_2$max by comparing different approaches and concluded that the most robust approach was that based on the sum of each value higher than 95% of $\dot{V}O_2$peak of the day (15). Importantly, the explanation above only serves as a justification of our methodological decision, which also has inherited limitations. Then, the alternative view that $\dot{V}O_2$peak was not achieved in the 4 trials discussed above cannot be dismissed and should, in fact, be considered carefully. Finally, it is important to mention that we found unexpected results for 1 subject for which the relative time spent at $\dot{V}O_2$peak during the 2 longest conditions (9 and 12 minutes) were far lower than the other individuals. After careful examination of subject's cardiorespiratory, metabolic, and perceptual responses, we were unable to find definitive explanation on why this variability occurred.

Practical Applications

Using the CP model to standardize exercise conditions, we compared the time spent at $\dot{V}O_2$peak at 4 predicted exercise durations (3, 6, 9, and 12 minutes) within the severe intensity domain. This study demonstrated that the time spent at $\dot{V}O_2$peak was longer during the longest exercise trials (9 and 12 minutes) compared with the shortest one (3 minutes), which was the fastest achieving $\dot{V}O_2$peak. It should be noted that the time spent at $\dot{V}O_2$peak was tested only for exercise durations between 3 and 12 minutes. Therefore, it remains unknown whether severe-exercise intensities that can be tolerated for longer than 12 minutes would elicit longer times at $\dot{V}O_2$peak. Moreover, in practice, these findings have important implications for establishing and improving the effectiveness of exercise training prescription that aims to maximize the time an individual spends at $\dot{V}O_2$peak. Yet there is no clear indication as to whether exercise intensities closest to CP would still permit accumulating more time at $\dot{V}O_2$peak when multiple bouts of exercise are performed. Indeed, interval training constitutes a more complex framework where the intensity and duration of the work and recovery intervals can be manipulated, which might alter the dynamics of the $\dot{V}O_2$ response and thus the time spent near $\dot{V}O_2$peak. Therefore, future studies are warranted to investigate the relationship between time at $\dot{V}O_2$peak and CP-derived exercise duration during interval sessions. Nevertheless, in practice, the present results can be used as a reference to develop interval exercise training protocols by approximating the minimal necessary time to achieve $\dot{V}O_2$peak and the time spent at $\dot{V}O_2$peak for a given CP-derived exercise intensity. However, it is also essential to recognize that enhancing performance is not solely dependent on improving $\dot{V}O_2$ but also relies on metabolic, cardiovascular, respiratory, and neuromuscular adaptations, which can be achieved through exercising in various regions within the severe intensity domain.

Acknowledgments

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