Time to exhaustion at and above critical power in trained cyclists: The relationship between heavy and severe intensity domains

Temps d’épuisement à la puissance critique et au-dessus chez des cyclistes entraînés

R.D. de Lucas, K.M. de Souza*, V.P. Costa, T. Grossl, L.G.A. Guglielmo

Sports Center, Federal University of Santa Catarina, Physical Effort Laboratory, Florianópolis, CEP: 88040-900 Florianópolis (SC), Brazil

Received 3 December 2011; accepted 5 April 2012
Available online 31 October 2012

Summary

Objectives.—The aim of this study was to determine the physiological responses and time to exhaustion, at critical power and 5% above, in trained cyclists.

Equipments and methods.—Eleven male cyclists completed an incremental test, three constant work rate tests to exhaustion to determine critical power (CP), and finally two tests until exhaustion at CP and CP plus 5%.

Results.—The modeling of the power-inverse time relationship provided a mean critical power of 295 ± 39 W. Time to exhaustion at critical power was significantly higher than 5% above (22.9 ± 7.5 min versus 13.3 ± 5.8 min). Oxygen uptake, pulmonary ventilation, and blood lactate obtained at the end of the CP plus 5% exhaustion trial were not significantly different from the maximal variables. However, the physiological end values during the CP test were significantly lower compared to the incremental test.

Conclusions.—These data support the idea that CP in trained cyclists is the physiological index that estimates the boundary between heavy to severe exercise domains. Thus, when cyclists exercised at a power output 5% higher than CP, the VO2max was reached at the end of exercise.

© 2012 Elsevier Masson SAS. All rights reserved.

* Corresponding author.
E-mail address: kristophersouza@yahoo.com.br (K.M. de Souza).
1. Introduction

The hyperbolic relationship between work rate and time to exhaustion (TTE) is a fundamental property of exercise performance in humans [1–4] and rats [5,6]. Monod and Scherrer [1] first reported this hyperbolic relationship in a single muscle group, and this relationship was subsequently demonstrated during whole-body exercise, such as cycling [2], treadmill running [7], swimming [8], and rowing [9].

The work-rate asymptote of this hyperbolic relationship has been termed critical power (CP), whereas curvature constant (i.e. the total amount of work that can be performed above the CP) has been termed anaerobic work capacity (AWC) [1–4]. The parameters CP and AWC can also be derived through linear regression analysis after transformation of the hyperbolic relationship into a linear formulation by plotting total work done during the series of exercise tests versus TTE [1] or by plotting power output versus the inverse of TTE (P versus 1/TTE) [3,4,10].

Two decades ago, some studies aimed to better understand the definition of CP by investigating the intensity domains at which maximal oxygen uptake (VO\textsubscript{2max}) can be attained [3,4]. It was demonstrated that CP represented the highest intensity that is sustainable for a prolonged duration without eliciting VO\textsubscript{2max}, that is, the lower boundary for severe exercise [3,4,11]. Accordingly, some authors observed a non-attainment of VO\textsubscript{2max} despite an oxygen uptake slow component (VO\textsubscript{2sc}) during exercise performed at CP [3,4,11–13].

However, the variability of methods proposed to determine CP has not provided the boundary for the heavy to severe exercise domain, since previous studies reported a variation of 24% depending on the CP mathematical model [14–16]. In a recent review, Dekerle et al. [17] highlighted that linear model P versus 1/TTE represents the best estimation of the CP concept, showing greater absolute value when compared to other 2-parameter models. Therefore, this model has been used to investigate the physiological responses during CP exercise [3,4,12,15].

However, few studies have analyzed both physiological responses and TTE at CP and above. Poole et al. [3] hypothesized that CP represented an intensity that was slightly above physiological steady state and, hence, would lead to VO\textsubscript{2max}. However, the authors found this not to be the case, and power needed to be increased by approximately 16 W (an average of 7% of CP) to elicit VO\textsubscript{2max} in a group of active subjects [3]. A subsequent study using trained cyclists investigated TTE at CP and found an average end value of 91% of VO\textsubscript{2max} [12].

To the best of our knowledge, no study has verified these physiological responses above CP in trained individuals with the aim of analyzing the lower limit of the severe domain. Since in trained subjects CP occurs at a work rate closer to maximal aerobic power output (P\textsubscript{max}) [18], we hypothesized that these subjects could reach VO\textsubscript{2max} at a lower percentage above CP (i.e. 5%) than active people. Thus, the aim of this study was to determine the physiological responses and TTE at CP (P versus 1/TTE) and 5% above (CP\textsubscript{5%}) in competitive cyclists.

2. Subjects

Eleven competitive male cyclists (mean ± SD: 20 ± 5 years; 71 ± 12 kg; 179 ± 7 cm) participated in the study. The cyclists had been training for and competing in endurance cycling races on a regular basis for a minimum of 4 years. At the time of testing, they were in the beginning of the yearly training program and were cycling approximately 400–450 km/wk. After being fully informed of the risks and stresses associated with the study, subjects gave their written informed consent to participate. The study was performed according to the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of the Federal University of Santa Catarina, Florianópolis, Brazil.
3. Experimental Protocol

Subjects were instructed to avoid any intake of caffeine or alcohol and strenuous exercise in 24 h preceding a test session and to arrive at the laboratory in a rested and fully hydrated state, at least 3 h postprandial. All tests were performed at the same time of day in a controlled environmental laboratory condition (19–22 °C; 50–60% RH) to minimize the effects of diurnal biological variation on the results [19]. Athletes reported to the laboratory to perform:

- an incremental continuous cycling test for the measurement of VO2max and Pmax;
- three constant work rate tests in random order to determine TTE at 95, 100, and 110% Pmax to calculate CP using the linear model P versus 1/TTE [3];
- two sessions to determine TTE at CP and CP+5%.

Subjects performed only one test on any given day, and the tests were each separated by 24–48 h but completed within a period of two weeks.

3.1. Procedures

3.1.1. Materials

All exercise testing was performed on the cyclist’s own bicycle, which was mounted on the Computrainer® ergometer system (Computrainer® Pro 3D, RacerMate, Seattle, Washington, USA). The rear wheel was inflated to 800 kPa after which the system’s load generator was calibrated to a rolling resistance between 0.88 and 0.93 kg. This calibration procedure was done before and directly after the 15-min warm-up to ensure accurate calibration as recommended by Davidson et al. [20]. Respiratory and pulmonary gas exchange variables were measured breath-by-breath during all protocols (Quark PFT ergo, Cosmed, Rome, Italy). Before each test, the O2 and CO2 analysis systems were calibrated using ambient air and a gas of known O2 and CO2 concentration according to the manufacturer’s instructions, while the Quark PFT ergo turbine flow-meter was calibrated using a 3-L syringe (Calibration Syringe 3-L, Cosmed, Rome, Italy). Heart rate (HR) was continuously recorded during the tests by a HR monitor incorporated into the gas analyzer. Breath-by-breath oxygen uptake (VO2) and HR data were reduced to 15 s stationary averages throughout the tests (Data Management Software, Cosmed, Rome, Italy). Capillary blood samples (25 μl) were obtained from the ear lobe of each subject during all tests, and the blood lactate concentration ([lac]) was measured using an electrochemical analyzer (YSL 2700 STAT, Yellow Springs, Ohio, USA). The analyzer was calibrated in accordance with the manufacturer’s recommended procedures.

3.1.2. Incremental exercise testing

The incremental test started at 100 W and was continuously increased by 30 W every 3 min until volitional exhaustion [21]. Blood samples were collected during the final 15 s of every 3 min. Each cyclist was verbally encouraged to undertake maximum effort. VO2max was considered as the highest value obtained in a 15 s interval. The attainment of VO2max was defined using the criteria proposed by Lacour et al. [22]. Pmax was determined according to the equation $P_{\text{max}} = \text{power output last stage completed} \times \left[ \frac{t}{s} \right]$, where ‘t’ is the time of the uncompleted stage [23].

3.1.3. Determination of critical power

The CP was determined using three TTE values measured from the constant work rate tests (95, 100, and 110% Pmax). Both before each test, subjects completed a 10-min warm-up at 50% Pmax followed by a 5-min rest, after which the subjects were instructed to perform the required power output until they were unable to maintain the fixed power output. All exercise testing was performed at the cyclist’s preferred cadence. Subjects were verbally encouraged to undertake maximum effort for as long as possible throughout the tests. Cardiorespiratory variables were measured continuously during all protocols. TTE was measured to the nearest second. The linear model P versus 1/TTE was used to determine CP [24]: $P = (\text{AWC/TTE}) + \text{CP}$; where TTE = time to exhaustion; AWC = anaerobic work capacity; P = power output; CP = critical power.

3.1.4. Time to exhaustion at critical power and 5% above critical power

After a 10-min warm-up at power output 50% Pmax followed by a 5-min rest, subjects were instructed to perform the required power output (CP and CP+5%) to exhaustion. Cardiorespiratory variables were measured continuously during tests. Both exercise tests were stopped when the cadence fell below the preferred cadence and/or until volitional exhaustion. Athletes were blinded to the time elapsed on testing protocols. Blood samples were collected in the 5th min and at exhaustion to determine [lac]. TTE was measured to the nearest second. The VO2gc was computed as the difference between VO2 at exhaustion and the 3rd min of the exercise [15].

3.1.5. Statistical analysis

All data throughout are expressed as mean ± SD. The Shapiro-Wilk test was applied to ensure a Gaussian distribution of the data. One-way repeated-measures ANOVA was used to compare the maximal physiological variables from incremental exercise test with end physiological variables from the TTE tests at CP and 5% above. Two-way repeated-measures ANOVA was used across intensities (CP and CP+5%) and relative time (25%, 50%, 75%, and 100%). In case of a non-significant interaction, only the main effect of the test was considered. When intensity-time interactions were significant, post hoc one-way ANOVA was performed on the relevant data, and the Bonferroni-adjusted paired t-tests were used as appropriate to identify differences between responses at specific time points. The level of significance was set at $P<0.05$.

4. Results

$\text{VO2}_{\text{max}}$, $P_{\text{max}}$, HR$_{\text{max}}$, VE$_{\text{max}}$, and [lac]$_{\text{max}}$ values were $68.8 \pm 5.6 \text{ml/kg/min}$, $344 \pm 43 \text{W}$, $196 \pm 7 \text{bpm}$, $164.1 \pm 26.4 \text{l/min}$, and $12.2 \pm 1.9 \text{mmol/l}$, respectively. TTE at 95, 100, and 110% Pmax values were $9.9 \pm 3.8$, $6.8 \pm 2.7$, and $3.8 \pm 2.0 \text{min}$, respectively. The modeling of the power-inverse time relationship (adjusted
The mean physiological responses during exercise at CP and CP+5% are shown in Fig. 1. Two-way ANOVA with repeated measures across intensity and relative time revealed no significant intensity-by-time interaction for any dependent variables (VO$_2$, $r = 0.99$; VE, $r = 0.97$; HR, $r = 0.96$). However, the main effect showed that VO$_2$ increased over time until 75% of TTE. In contrast, VE and HR increased over the entire duration of the tests. We did not find significant differences in the VO$_2$ between the intensities (247 ± 82 ml/min versus 222 ± 106 ml/min for CP and CP+5%, respectively).

5. Discussion

The aim of this study was to determine the physiological responses during TTE at CP and CP+5% in competitive cyclists. The main finding was that when subjects were exercising at intensities slightly above CP (i.e. 5%), VO$_{2max}$ was attained. Few studies have analyzed physiological responses at CP and/or above in trained cyclists [12,25,26]. The mean value of CP observed in our study was ~300 W, unlike classic studies by Poole et al. [3,4] conducted with physically active subjects (CP = ~200 W). The subjects different fitness levels could change the percentage above CP in which VO$_2$ was reached and hence the lower boundary of severe domain [18].

In a recent review, Jones et al. [27] highlighted that CP was found to occur at 80% of VO$_{2max}$, approximately midway between the gas exchange threshold and VO$_{2max}$ (50% Δ). In contrast, Caputo and Denadai [18] showed, in trained cyclists (CP = ~303 W), that the upper boundary of the heavy intensity domain lies at approximately 75% Δ, suggesting that aerobic training modifies the relationship between CP and the difference between first lactate threshold and VO$_{2max}$. In the present investigation, we found an average of 65% Δ, and this value could be explained by the fact that experimental procedures were held in the beginning of the competitive season. Nevertheless, the athletes had at least 4 years of training on a regular basis, ensuring a good development of aerobic fitness.

To our knowledge, this is the first study in trained cyclists (VO$_{2max} = 68.8$ ml/kg/min) that has analyzed TTE and VO$_2$ response at and above CP. We have used a fixed percentage above CP (i.e. 5%) instead of the fixed work rate used by others [11,28], i.e. 10 or 15 W above CP to measure physiological responses in untrained subjects.

The studies published by Poole et al. [3,4] have been misunderstood by others [11,12,29] since the percentage

![Figure 1](image-url)
above CP cited does not represent the actual value. In fact, Poole et al. [3,4] used 5% of peak power output from the incremental test to calibrate the intensity above CP. Consequently, the subjects exercised at different percentages above CP (i.e. 6–8%), values slightly different than those aforementioned authors have described (i.e. 8–11% above CP) about studies from Poole et al. [3,4]. It is important to note that the imprecision of the CP estimate would influence VO₂ and [lac] responses, as well as TTE. These facts lead us to choose a fixed percentage over a fixed workload, since our results showed an average SEE of 2.5 ± 1.4% (7.5 ± 4.2 W) and hence ensured that subjects cycled just above CP.

When exercise was performed at CP, 15%, the TTE decreased approximately 40% compared with TTE at CP. However, the VO₂ at the end of exercise was significantly different from the CP test but not different from VO₂max (Fig. 1A). The HR values were very close to HRmax (~97%), and VE had no significant differences from VEmax (Figs. 1B and C, respectively). Also, the end [lac] was not substantially different from the incremental exercise testing. Brickley et al. [12] reported that the VO₂ at CP averaged 91% of VO₂max. In agreement with this study, the VO₂ response at CP indicated a progressive increase reaching 94% of VO₂max at exhaustion. Therefore, the data from our study support the suggestions that VO₂max is not elicited at CP and that the intensity of exercise needs to be increased by about 5% for VO₂max to be reached.

This is in accordance with the description of the severe domain (> CP), in which both VO₂ and [lac] do not stabilize but rise continuously over time until VO₂max is reached and/or fatigue resulting from the metabolic acidosis terminates exercise [30]. The short tolerance observed during exercise above CP has been associated with the gradual depletion of AWC, which is determined by the limited supplies of energy [2]. A previous study performed with an exercise intensity of 10% above CP found a gradual depletion of phosphocreatine and pH and an increase in inorganic phosphate [31]. The TTE observed at CP agreed with studies on trained cyclists that indicate the overestimation of maximal lactate steady state [12, 32–34]. Housh et al. [35] reported that TTE at CP was 33.3 min ± 14.4 s. Brickley et al. [12] found that TTE ranges from 20.1 min to 40.4 min during CP tests. In the study by Brickley et al. [12], the subjects who had the highest VO₂max and the highest CP reached their exhaustion time earlier (r = -0.78; r = -0.92 P < 0.05, respectively). In the present study, we failed to demonstrate any significant correlation between TTE and VO₂max, PO₂max or CP.

The identification of meaningful markers of the intensity at which exercise is performed is useful for training programs and studies designed for athletes. However, the methods used to determine the CP may demarcate the exercise intensity domains at a different power output. Some studies have reported that CP estimates differ significantly depending upon the mathematical model used to determine the power-time relationship (data can vary by up to 24%) [14, 36]. More recently, Bull et al. [15] found in runners that critical velocity estimates from the five models varied by 18%. Therefore, these studies support the idea that the linear model used in our study is acceptable to estimate the boundary of heavy to severe exercise domain. Thus, CP could be an important and practical index to prescribe interval training between these domains.

6. Conclusion

The data from our study support the idea that CP determined in trained cyclists (CP = ~300 W) is the physiological index that estimates the boundary between heavy to severe exercise intensity domains. In addition, the physiological variables did not reach steady state during the CP test to exhaustion, but the VO₂max was not elicited. However, when cyclists had exercised at a power output 5% higher than CP, the VO₂max was reached at the end of exercise.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

References


[18] Caputo F, Denadai BS. Does the 75% of the difference between the VO\textsubscript{2} at lactate threshold and VO\textsubscript{2}max lie at severe intensity domain in well trained cyclists? Sci Sports 2009;24(5):257–61.


