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ORIGINAL ARTICLE

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

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Physiological responses;
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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 VO_{2max} was reached at the end of exercise.

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MOTS CLÉS
Réponse physiologique ;
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Résumé

Objectifs. — Le but de cette étude est de déterminer les réponses physiologiques et le temps d'épuisement, à la puissance critique et à 5 % au-dessus de la puissance critique pour des cyclistes entraînés.

Équipement et méthode. — Onze cyclistes masculins ont complété un test progressif, trois tests à charge constante jusqu'à épuisement pour déterminer les puissances critiques et enfin deux tests jusqu'à épuisement à la puissance critique et puissance critique plus 5 %.

Résultats. — La modélisation de la relation entre puissance inverse et le temps a fourni une puissance critique de 295 ± 39 W. Le temps jusqu'à l'épuisement à la puissance critique a été considérablement plus élevé que 5 % au-dessus (22,9 ± 7,5 min versus 13,3 ± 5,8 min). La consommation d'oxygène, la ventilation pulmonaire et le lactate sanguin obtenu à la fin de l'essai de l'épuisement à la puissance critique +5 % n'ont pas été considérablement différents des variables maximales. Néanmoins, les valeurs physiologiques finales pendant les puissances critiques test ont été considérablement inférieures comparativement au test progressif.

Conclusions. — Les informations appuient l'idée que la puissance critique des cyclistes entraînés est l'index physiologique qu'estime la limite entre le domaine d'exercice lourd et sévère. Donc, quand les cyclistes sont entraînés à une puissance 5 % plus élevée que la puissance critique, la consommation maximale d'oxygène a été atteinte à la fin de l'exercice.

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_{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_{2max}, that is, the lower boundary for severe exercise [3,4,11]. Accordingly, some authors observed a non-attainment of VO_{2max}, despite an oxygen uptake slow component (VO_{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_{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_{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_{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_{max}) [18], we hypothesized that these subjects could reach VO_{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 ($CP_{+5\%}$) 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 VO_{2max} and P_{max};
- three constant work rate tests in random order to determine TTE at 95, 100, and 110% P_{max} 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 PFTergo, Cosmed, Rome, Italy). 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 Quark PFTergo 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 (VO_2) 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. VO_{2max} was considered as the highest value obtained in a 15 s interval. The attainment of VO_{2max} was defined using the criteria proposed by Lacour et al. [22]. P_{max} was determined according to the equation P_{max} (W) = power output last stage completed (W) + [t (s)/step duration (s) × step increment (W)], 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% P_{max}). Before each test, subjects completed a 10-min warm-up at 50% P_{max} 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 = (AWC/TTE) + 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% P_{max} 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 VO_{2SC} was computed as the difference between VO_2 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-by-time interactions were significant, post hoc one-way ANOVA was performed on the relevant data, and the Bonferroni-adjusted paired t-test was used as appropriate to identify differences between responses at specific time points. The level of significance was set at $P < 0.05$.

4. Results

VO_{2max}, P_{max}, HR_{max}, VE_{max}, and $[lac]_{max}$ values were 68.8 ± 5.6 ml/kg/min, 344 ± 43 W, 196 ± 7 bpm, 164.1 ± 26.4 l/min, and 12.2 ± 1.9 mmol/l, respectively. TTE at 95, 100, and 110% P_{max} values were 9.9 ± 3.8, 6.8 ± 2.7, and 3.8 ± 2.0 min, respectively. The modeling of the power-inverse time relationship (adjusted

$r^2 = 0.95 \pm 0.05$) provided mean CP values of 295 ± 39 W (SEE = 7.5 ± 4.2 W). TTE at CP (22.9 ± 7.5 min) was significantly higher ($P < 0.01$) than TTE at $CP_{+5\%}$ (13.3 ± 5.8 min). The ranges of the TTE values for the two intensities were 15.6—42.5 min at CP and 10.3—30.1 min at $CP_{+5\%}$. In addition, TTE values from the two intensities were highly correlated ($r = 0.90$, $P < 0.05$). However, no other variable was associated with TTE at CP and $CP_{+5\%}$.There was no significant difference between VO_2 (68.0 ± 6.3 ml/kg/min), VE (155.8 ± 26.6 l/min), and [lac] (11.0 ± 2.4 mmol/l) obtained at the end of $CP_{+5\%}$ exhaustion trial compared to the incremental test. However, the end value of VO_2 (64.8 ± 5.7 ml/kg/min), VE (145.7 ± 22.5 l/min), and [lac] (9.5 ± 2.1 mmol/l) during the CP test was significantly lower than VO_{2max}, VE_{max}, and $[lac]_{max}$, respectively. The VO_2 at exhaustion averaged 94% of VO_{2max}. The end HR values at CP (190 ± 8 bpm) and $CP_{+5\%}$ (189 ± 7 bpm) were significantly lower than the HR_{max} ($P < 0.01$).

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, $P = 0.99$; VE, $P = 0.97$; HR, $P = 0.96$). 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_{2SC} between the intensities (247 ± 82 ml/min versus 222 ± 106 ml/min for CP and $CP_{+5\%}$, respectively).

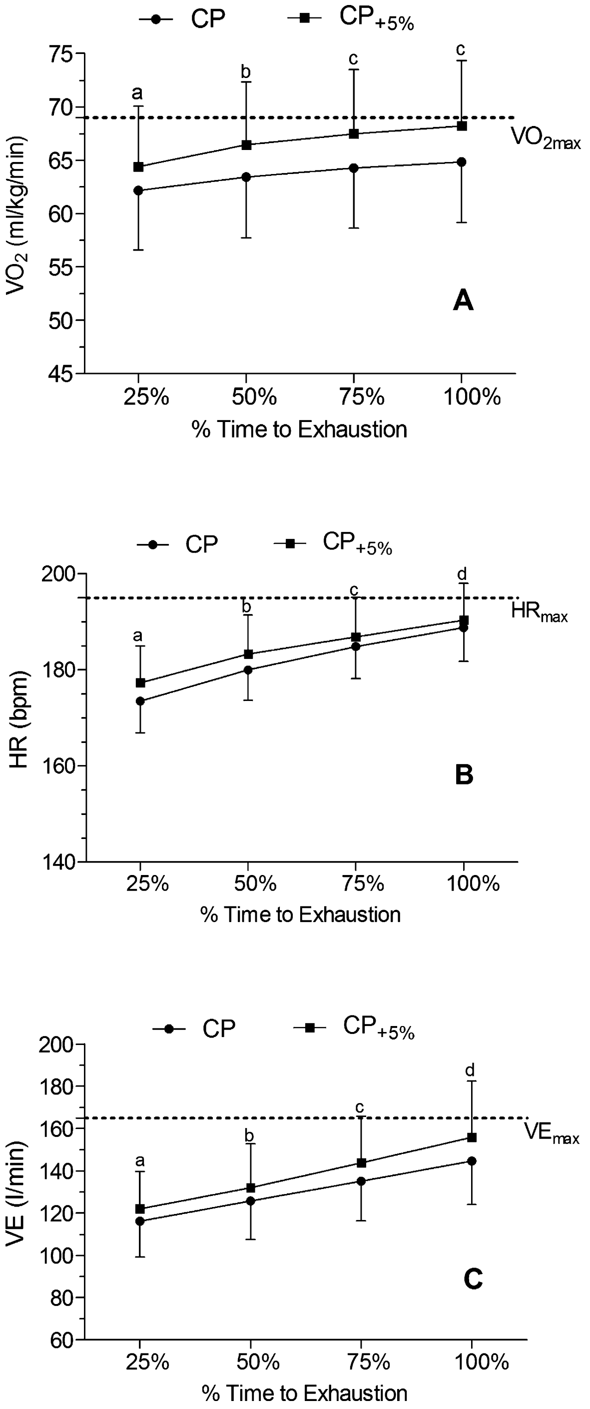

Figure 1 Cardiorespiratory measures (mean, SD) during time to exhaustion at critical power (CP) and 5% above ($CP_{+5\%}$). VO_2 (A); HR (B); VE (C); different letters mean significant difference over time ($P < 0.05$).

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_{2max} 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 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 VO_2 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 $2.5 \pm 1.4\%$ (7.5 ± 4.2 W) and hence ensured that subjects cycled just above CP.

When exercise was performed at $CP_{+5\%}$, the TTE decreased approximately 40% compared with TTE at CP. However, the VO_2 at the end of exercise was significantly different from the CP test but not different from VO_{2max} (Fig. 1A). The HR values were very close to HR_{max} (~97%), and VE had no significant differences from VE_{max} (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 VO_2 at CP averaged 91% of VO_{2max}. In agreement with this study, the VO_2 response at CP indicated a progressive increase reaching 94% of VO_{2max} at exhaustion. Therefore, the data from our study support the suggestions that VO_{2max} is not elicited at CP and that the intensity of exercise needs to be increased by about 5% for VO_{2max} to be reached.

This is in accordance with the description of the severe domain (> CP), in which both VO_2 and [lac] do not stabilize but rise continuously over time until VO_{2max} 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 VO_{2max} 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 VO_{2max}, P_{max} 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 VO_{2max} was not elicited. However, when cyclists had exercised at a power output 5% higher than CP, the VO_{2max} was reached at the end of exercise.

Disclosure of interest

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

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