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Maximal power output during incremental cycling test is dependent on the curvature constant of the power-time relationship

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1 **Maximal power output during incremental cycling test is dependent on the**
2 **curvature constant of the power-time relationship**

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15

1 Abstract

2 The aim of this study was to investigate whether the maximal power output
3 ($P_{\max}$) during an incremental test (INC) was dependent on the curvature constant
4 (W') of the power-time relationship. Thirty healthy male subjects ($VO_{2\max} = 3.58 \pm$
5 $0.40 \text{ L}\cdot\text{min}^{-1}$) performed a ramp incremental cycling test to determine the $VO_{2\max}$
6 and $P_{\max}$, and four constant work rate tests to exhaustion in order to estimate two
7 parameters from the modeling of the power-time relationship (i.e., critical power -
8 CP and W'). Afterwards, the participants were ranked according to their magnitude
9 of W' . The median third was excluded to form a high W' group (HIGH, $n = 10$), and
10 a low W' group (LOW, $n = 10$). $VO_{2\max}$ (3.84 ± 0.50 vs. $3.49 \pm 0.37 \text{ L}\cdot\text{min}^{-1}$) and CP
11 (213 ± 22 vs. $200 \pm 29 \text{ W}$) were not significantly different between HIGH and LOW,
12 respectively. However, $P_{\max}$ was significantly greater for the HIGH ($337 \pm 23 \text{ W}$)
13 than for the LOW ($299 \pm 40 \text{ W}$). Thus, in physically active individuals with similar
14 aerobic parameters, W' influences the $P_{\max}$ during INC.

15 **Key words:** exercise performance, cycling, endurance, fatigue, critical power,
16 ramp incremental test.

17

1 Introduction

2 Maximal oxygen uptake (VO_{2max}) and maximal power output (P_{max}), both
3 determined during ramp or step incremental tests (INC), have been used
4 extensively for training prescription (Green et al. 2013) and endurance
5 performance prediction (McNaughton et al. 2006). P_{max} is influenced by both the
6 physiological parameters (e.g., exercise economy, anaerobic capacity and muscle
7 power) (Jones and Carter 2000), and exercise protocols used for its determination
8 (Bentley and McNaughton 2003). There is a consensus that while VO_{2max} remains
9 unchanged, the P_{max} is protocol-dependent (i.e., ramp slopes or step increments
10 and durations) (Bentley and McNaughton 2003). Overall, it has been shown that
11 the ramp incremental tests result in greater P_{max} than that attained during the step
12 incremental tests (Zuniga et al. 2012), and that steeper ramps elicit higher P_{max}
13 (Morton 2011).

14 On the other hand, the identification of the factors influencing the inter-
15 individual variability of P_{max} remains a topic of intense debate. It has been
16 proposed that P_{max} reflects the association between VO_{2max} and exercise economy
17 (Billat et al. 2003). However, Rønnestad et al. (2014) found in a group of elite
18 cyclists that P_{max} was increased after heavy strength training, while no significant
19 change was observed in VO_{2max} and gross efficiency. Thus, other metabolic (e.g.,
20 anaerobic capacity) and neuromuscular (e.g., muscle power) variables have been
21 also associated with P_{max} (Jones and Carter 2000), although direct evidence for
22 this relationship is limited or equivocal.

23 Regarding these likely associations, some insights can be obtained from
24 the critical power concept. Exercise tolerance (T_{lim}) during high-intensity exercise
25 can be predicted by the curvature constant (W') of the power-time relationship

1 (Jones et al. 2010). The asymptote of this relationship, termed critical power (CP),
2 is considered to be the lower boundary of the severe-intensity domain (equation
3 1).

$$4 \quad T_{lim} = W' / (P - CP) \quad (1)$$

5 where P represents the power output above CP. Evidence shows that W' dictates
6 the T_{lim} during severe-intensity exercise, with exercise intolerance coinciding with
7 the accumulation of metabolites that are linked to the process of muscle fatigue
8 until some critical concentration is attained (i.e., [PCr], [P_i], and [H⁺]) (Vanhatalo et
9 al. 2010). Applying the CP model (CP and W' as constants and the ramp slope as
10 variable) to INC with different ramp slopes, Morton (2011) has demonstrated why
11 steeper ramps determining higher P_{max} according to equation 2.

$$12 \quad T_{lim} = CP / S + \sqrt{2W' / S} \quad (2)$$

13 where S represents the ramp slope. Indeed, considering that W' represents a fixed
14 amount of work that can be performed above CP, irrespective of the rate of its
15 expenditure (Jones et al. 2010), steeper ramps, and consequently, lower time
16 above CP, can determine higher P_{max} (Morton 2011). According to this data, the
17 magnitude of W' should be able to discriminate the P_{max} of individuals with similar
18 CP values. Thus, a likely factor that determines P_{max} during INC is therefore W',
19 although this has never been directly verified.

20 Therefore, our main objective was to compare the P_{max} between two groups
21 having similar CP but different W'. For this purpose, participants were ranked
22 according to their W' and the median third was excluded to form a low W' group
23 (LOW) and a high W' group (HIGH). It was hypothesized that the higher the W',
24 the higher the P_{max} obtained during INC. In addition, the correlations between P_{max}
25 and variables derived from INC and CP model were analyzed.

1

2 **Material and methods**

3 **Subjects**

4 Thirty healthy male subjects (mean $\pm$ SD; age, 25.9 ± 3.7 years; weight,
5 77.5 ± 8.8 kg; height, 177.4 ± 6.6 cm) volunteered to participate in this study. The
6 subjects participated in exercise at a recreational level and were familiar with cycle
7 ergometry and exercise testing procedures used in our laboratory. After being fully
8 informed of the risks and stresses associated with the study, the subjects gave
9 their written informed consent to participate. The experimental protocol was
10 approved by the local Ethics Committee of the University and was conducted in
11 accordance with the Declaration of Helsinki.

12

13 **Study design**

14 The subjects were required to visit the laboratory on five different
15 occasions. Each subject performed the following testing stages: 1) a submaximal
16 step incremental test (four to five work rates) to determine the lactate threshold
17 (LT), followed by a maximal ramp incremental test for the measurement of VO_{2max}
18 and P_{max} ; and; 2) four maximal constant work rate tests performed to exhaustion at
19 75%, 85%, 95% and 105% P_{max} for CP and W' determination. The subjects were
20 instructed to avoid any intake of caffeine or alcohol and strenuous exercise in the
21 24 h preceding a test session and to arrive at the laboratory in a rested and fully
22 hydrated state, at least 3 h postprandial. All tests were performed at the same time
23 of day in a controlled environmental laboratory condition ($19-22^{\circ}C$; 50-60%RH) to
24 minimize the effects of diurnal biological variation on the results. With exception of
25 the submaximal and maximal incremental exercise tests, which were performed on

the same day, the 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. Upon study completion, the participants were ranked according to their magnitude of W' . The median third was excluded to form a high W' group (HIGH, $n = 10$), and a low W' group (LOW, $n = 10$). There was no overlap in the W' values between the groups.

Equipment

All tests were performed on an electromagnetically braked cycle ergometer (Excalibur Sport, Lode BV, Groningen, Netherlands). For all stages, pedal cadence was selected at 70 ± 1 rpm. Marsh and Martin (1997) reported that individuals without cycling training maintained a preferred pedal cadence between 65 and 80 rpm. Respiratory and pulmonary gas exchange variables were measured continuously using a breath-by-breath analyzer (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). Breath-by-breath VO_2 data were analyzed throughout the tests (Data Management Software, Cosmed, Rome, Italy). Capillary blood samples (25 μ l) were obtained from the earlobe of each subject and the blood lactate concentration ($[La]$) 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.

1 Submaximal and maximal incremental tests

2 Initially, each subject performed a submaximal step incremental test to
3 determine LT. The test started at 60 W and was increased by 20 W every 3 min
4 during four to five stages. Capillary blood samples were collected within the final
5 20 s of each stage for an immediate [La] determination. The LT was determined
6 from the relationship between [La] and work rate and was considered as the first
7 sudden and sustained increase in [La] above resting concentrations (Carter et al.
8 2000). After 30 min of resting, the subjects performed a maximal ramp incremental
9 test for the measurement of $\text{VO}_{2\text{max}}$ and P_{max} . This test started at 90% of LT during
10 the first 4 min and was thereafter continuously increased by a rate of $25 \text{ W} \cdot \text{min}^{-1}$
11 until the volitional exhaustion. Each subject was verbally encouraged to undertake
12 maximal effort. Breath-by-breath oxygen uptake (VO_2) data was reduced to 15 s
13 stationary averages and the $\text{VO}_{2\text{max}}$ was considered as the highest average 15 s
14 VO_2 value recorded during the ramp incremental test. The P_{max} was considered as
15 the highest power output attained in the ramp incremental test.

16

17 Determination of CP and W'

18 The subjects performed four maximal constant work rate tests until
19 exhaustion at 75%, 85%, 95% and 105% P_{max} . These work rates were chosen to
20 induce a Tlim over a range of times between 3 and 15 min (Vanhatalo et al. 2010).
21 Each test started with a 5 min warm-up at LT intensity followed by a 5 min of rest.
22 Previous exercise performed at moderate-intensity domain (i.e., $\leq \text{LT}$) does not
23 modify both the magnitude of W' and Tlim within severe-intensity domain (i.e., $>$
24 CP) (Wilkerson et al. 2003). Further, after 3 min at 20 W the power output was
25 adjusted to one of the previously established work rates and the subjects were

instructed to perform until they were unable to maintain the required work rate. Timing began when the pedal cadence reached 70 rpm and stopped when the subject could not maintain a pedal cadence of higher than 67 rpm despite verbal encouragement (Caputo and Denadai 2008). The Tlim was measured to the nearest second.

Data analysis

Individual CP and W' estimates were derived from the four prediction trials by least-squares fitting of the following regression models:

1) Nonlinear power output (P) vs. time to exhaustion (Tlim):

$$Tlim = W' / (P - CP) \quad (1)$$

2) Linear work (W) vs. time to exhaustion (Tlim):

$$W = (CP \times Tlim) + W' \quad (3)$$

3) Linear power output (P) vs. 1 / time to exhaustion (Tlim):

$$P = (W' / Tlim) + CP \quad (4)$$

The CP and W' estimates from the three equations were compared in order to select the best fit using the model associated with the lowest standard error for CP (SEE) (Vanhatalo et al. 2010). The CP and W' were applied in equation 2 in order to predict Tlim for the ramp incremental test ($S = 0.41 \text{ W} \cdot \text{s}^{-1}$) (Morton 2011).

The $P_{\max}$ was estimated from equation 5:

$$P_{\max} = S \times Tlim \quad (5)$$

Statistical analysis

All data throughout are expressed as mean $\pm$ SD. The Shapiro-Wilk test was applied to ensure a Gaussian distribution of the data. Student's unpaired t-test

1 was used in unpaired comparisons. Pearson's product-moment correlation
2 coefficient and stepwise multiple regression was used to determine the best
3 independent variables to predict $P_{\max}$ for the overall sample only. Paired t-tests
4 and Pearson's product-moment correlation coefficient were used to examine the
5 relationship between actual and predicted $P_{\max}$ for INC. Analyses were carried out
6 using SPSS (v. 20.0, Chicago, Illinois, USA). The level of significance was set at p
7 ≤ 0.05 .

8

9 **Results**

10

11 **Submaximal and maximal incremental tests**

12 Maximal and submaximal variables obtained during INC are presented in
13 Table 1. The $VO_{2\max}$ and LT were not significant different between HIGH and LOW
14 groups. The $P_{\max}$ was significantly greater in the HIGH than in the LOW group ($p <$
15 0.05).

16

17 **Determination of the power-time relationship**

18 There were no differences in parameter estimates derived from the three
19 fitting models. This goodness-of-fit for both nonlinear and linear regressions was
20 confirmed by R^2 -values > 0.98 . The 95% CIs associated with the estimated
21 parameters of the power-time relationship were 2.7 to 5.1 W and 0.9 to 1.4 kJ for
22 CP and W' , respectively. The CP was not significantly different between the HIGH
23 and LOW groups. The CP relative to $P_{\max}$ and W' were significantly different
24 between the HIGH and LOW groups ($p < 0.05$).

1 The actual $P_{\max}$ for INC (317 ± 33 W; range = 217-383 W) was not
2 significantly different from the predicted $P_{\max}$ (320 ± 28 W; range = 240-371 W),
3 and these values were highly correlated ($r = 0.94$, $p < 0.001$; see Fig. 1). The
4 correlations between $P_{\max}$ and $VO_{2\max}$ ($r = 0.61$), $P_{\max}$ and CP ($r = 0.89$) and
5 between $P_{\max}$ and W' ($r = 0.55$) in the total sample were statistically significant ($p <$
6 0.05). A stepwise multiple regression analysis from the overall sample ($n = 30$)
7 revealed that 80.7% of the variance for $P_{\max}$ could be explained by CP alone ($F =$
8 113.0 , $p < 0.001$), and the addition of W' to the prediction equation increased it
9 significantly (partial $F = 6.8$, $p < 0.01$) to 89.5% of the variance. Moreover, the
10 difference between $P_{\max}$ and CP was significantly correlated with W' ($r = 0.73$, $p <$
11 0.001).

13 Discussion

14 The principal finding of this study was that W' influences $P_{\max}$ in physically
15 active individuals that had similar aerobic parameters (LT, CP and $VO_{2\max}$). Similar
16 to previous studies (Chidnok et al. 2013; Morton 2011), we have demonstrated
17 that CP and W' accounted for $\sim 90\%$ of the variation in $P_{\max}$, confirming that CP
18 model can be used to predict different parameters (e.g., T_{lim} , CP and $P_{\max}$) during
19 INC. Moreover, CP/ $P_{\max}$ was lower in the HIGH group and the difference between
20 $P_{\max}$ and CP was significantly related to W' . These data confirm and extend the
21 proposal that the W' determines T_{lim} above CP, with voluntary exhaustion
22 coinciding with both depletion of muscle energy substrates (i.e., [PCr]) and the
23 attainment of $VO_{2\max}$ (Chidnok et al. 2013; Vanhatalo et al. 2010).

24 The CP model has been applied to both constant-work rate exercise (CWR)
25 and INC. Morton et al. (1997) have shown that CP and W' estimated during INC

1 were not different from those derived from conventional method (i.e., CWR). More
2 recently, Chidnok et al. (2013) also found that CP model could accurately predict
3 the performance (i.e., T_{lim}) during INC. In line with these studies, it was found that
4 the actual P_{max} for INC was not significantly different from predicted P_{max} and they
5 were highly correlated. Therefore, these results suggest some important
6 applications. Firstly, it is possible to apply the CP model to estimate different
7 parameters (e.g., T_{lim} , CP and P_{max}) during INC. Moreover, exercise in/tolerance
8 during INC and CWR performed within severe-intensity domain seems to be
9 determined by shared putative physiological mechanisms. Thus, these exercise
10 protocols (INC and CWR) could provide similar insights into the nature of exercise
11 intolerance in health and disease. Finally, CP was the best predictor of P_{max} .
12 Interestingly, Greco et al. (2012) verified in untrained subjects that CP expressed
13 as a unit of metabolic rate (i.e., VO_2) was highly correlated ($r = 0.98$) with VO_{2max} ,
14 suggesting that these variables could be determined by similar mechanisms. Thus,
15 the different units utilized to express CP, P_{max} and VO_{2max} , could explain the lower
16 relationship between P_{max} and VO_{2max} observed in the present study. As
17 mechanical variables, CP and P_{max} are determined by metabolic rate and exercise
18 economy, while VO_{2max} expresses only the former.

19 Several variables (e.g., VO_{2max} , exercise economy and VO_2 kinetics) have
20 been utilized to explain the inter-individual variability of P_{max} . However, the actual
21 contribution for some of them is still obscure (e.g., anaerobic capacity and muscle
22 power) (Jones and Carter 2000). There is a consensus that P_{max} reflects the
23 interaction between VO_{2max} and exercise economy. However, some recent
24 interventional studies have challenged the contribution of VO_{2max} and exercise
25 economy to explain the individual variability of P_{max} . In trained cyclists, Rønnestad

et al. (2014) have shown that $P_{\max}$ was increased after a strength-training period, while both $VO_{2\max}$ and gross efficiency were unchanged. In addition, Sawyer et al. (2014) found that $P_{\max}$ (~ 8%), $T_{\lim}$ at severe-intensity domain (39%) and W' (~ 40-60%) were improved after 8 weeks of strength training, whereas CP and $VO_{2\max}$ were not significantly modified. Our data are in line with these studies, demonstrating that $T_{\lim}$ during severe-intensity exercise (CWR and INC) can be modified with no corresponding changes in aerobic parameters ($VO_{2\max}$ and CP). In these conditions, W' is a determinant of $T_{\lim}$, and consequently, $P_{\max}$ during INC. Despite the interesting findings presented herein, the physiological basis of W' remains controversial (Dekerle et al. 2006; Vanhatalo et al. 2010). Our results add support to the suggestion that W' may be related to the magnitude (i.e., the relative distance between CP and $VO_{2\max}$) of the severe-intensity domain. However, the magnitude of W' has also been associated with the accumulation of metabolites (i.e., $[P_i]$ and $[H^+]$) related with muscle fatigue (Vanhatalo et al. 2010) and / or the amplitude of the VO_2 slow component (Murgatroyd et al. 2011). Using an elegant design (i.e., blood flow occlusion), Broxterman et al. (2015) demonstrated that rather than representing an anaerobic capacity (i.e., a constant store of anaerobic energy), the W' can vary across O_2 delivery conditions and might be determined by several mechanisms. Thus, future studies are necessary to elucidate the nature of W' .

It can be concluded that W' influences the $P_{\max}$ reached during INC in physically active individuals with similar aerobic parameters (LT, CP and $VO_{2\max}$). Moreover, the $P_{\max}$ for INC can be predicted by CP model (i.e., CP and W'). Thus, the depletion of W' and consequently the attainment of $VO_{2\max}$ seems to influence the exercise tolerance during INC.

26

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25

1 Table 1 – Physiological and mechanical parameters obtained during tests.

Variables	Overall	HIGH	LOW
	(N = 30)	(N = 10)	(N = 10)
VO _{2max} (L.min ⁻¹)	3.58 ± 0.40	3.84 ± 0.50	3.49 ± 0.37
P _{max} (W)	317 ± 33	337 ± 23	299 ± 40*
LT (W)	103 ± 26	92 ± 21	102 ± 17
CP (W)	206 ± 22	213 ± 22	200 ± 29
CP/P _{max} (%)	65.0 ± 3.1	63.2 ± 3.8	66.8 ± 2.5*
W' (kJ)	20.3 ± 4.3	25.1 ± 2.9	15.9 ± 1.8*

2 HIGH: high W' group; LOW: low W' group; VO_{2max}: maximal oxygen uptake; P_{max}:

3 maximal power output; LT: lactate threshold; CP: critical power; CP/P_{max}: critical

4 power relative to maximal power output; W': curvature constant of the power-time

5 relationship. * Significantly different between HIGH and LOW (p < 0.05).

6

1 **Figure Caption**

2

3 FIGURE 1. Actual versus predicted maximal power output ($P_{\max}$) during ramp
4 incremental test. Prediction was made using parameters derived from the power-
5 time relationship (i.e., CP and W') (Morton 2011). The solid line is the best-fit linear
6 regression, and the dashed line is the line of identity.

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