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

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Abstract

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

Key words: exercise performance, cycling, endurance, fatigue, critical power, ramp incremental test.
Introduction

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

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

Regarding these likely associations, some insights can be obtained from the critical power concept. Exercise tolerance ($T_{\text{lim}}$) during high-intensity exercise can be predicted by the curvature constant ($W'$) of the power-time relationship.
(Jones et al. 2010). The asymptote of this relationship, termed critical power (CP), is considered to be the lower boundary of the severe-intensity domain (equation 1).

\[ T_{\text{lim}} = W'/(P-CP) \]  

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

\[ T_{\text{lim}} = CP/S + \sqrt{(2W'/S)} \]  

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

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

Subjects

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

Study design

The subjects were required to visit the laboratory on five different occasions. Each subject performed the following testing stages: 1) a submaximal step incremental test (four to five work rates) to determine the lactate threshold (LT), followed by a maximal ramp incremental test for the measurement of \( \text{VO}_{2\text{max}} \) and \( P_{\text{max}} \); and; 2) four maximal constant work rate tests performed to exhaustion at 75%, 85%, 95% and 105% \( P_{\text{max}} \) for CP and \( W' \) determination. The subjects were instructed to avoid any intake of caffeine or alcohol and strenuous exercise in the 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. With exception of 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 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 PFTergo turbine flow
meter was calibrated using a 3 L syringe (Calibration Syringe 3 L, Cosmed, Rome,
Italy). Breath-by-breath VO₂ data were analyzed throughout the tests (Data
Management Software, Cosmed, Rome, Italy). Capillary blood samples (25 µl)
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.
Submaximal and maximal incremental tests

Initially, each subject performed a submaximal step incremental test to determine LT. The test started at 60 W and was increased by 20 W every 3 min during four to five stages. Capillary blood samples were collected within the final 20 s of each stage for an immediate [La] determination. The LT was determined from the relationship between [La] and work rate and was considered as the first sudden and sustained increase in [La] above resting concentrations (Carter et al. 2000). After 30 min of resting, the subjects performed a maximal ramp incremental test for the measurement of VO$_{2\text{max}}$ and $P_{\text{max}}$. This test started at 90% of LT during the first 4 min and was thereafter continuously increased by a rate of 25 W.min$^{-1}$ until the volitional exhaustion. Each subject was verbally encouraged to undertake maximal effort. Breath-by-breath oxygen uptake (VO$_2$) data was reduced to 15 s stationary averages and the VO$_{2\text{max}}$ was considered as the highest average 15 s VO$_2$ value recorded during the ramp incremental test. The $P_{\text{max}}$ was considered as the highest power output attained in the ramp incremental test.

Determination of CP and W'

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

\[ T_{lim} = W'/(P - CP) \]  

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

\[ W = (CP \times T_{lim}) + W' \]  

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

\[ P = (W'/T_{lim}) + CP \]  

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 W.s\(^{-1}\)) (Morton 2011).

The \( P_{\text{max}} \) was estimated from equation 5:

\[ P_{\text{max}} = S \times T_{lim} \]  

**Statistical analysis**

All data throughout are expressed as mean ± SD. The Shapiro-Wilk test was applied to ensure a Gaussian distribution of the data. Student’s unpaired t-test
was used in unpaired comparisons. Pearson’s product-moment correlation coefficient and stepwise multiple regression was used to determine the best independent variables to predict $P_{\text{max}}$ for the overall sample only. Paired t-tests and Pearson’s product-moment correlation coefficient were used to examine the relationship between actual and predicted $P_{\text{max}}$ for INC. Analyses were carried out using SPSS (v. 20.0, Chicago, Illinois, USA). The level of significance was set at $p \leq 0.05$.

Results

Submaximal and maximal incremental tests

Maximal and submaximal variables obtained during INC are presented in Table 1. The $\text{VO}_2\text{max}$ and LT were not significant different between HIGH and LOW groups. The $P_{\text{max}}$ was significantly greater in the HIGH than in the LOW group ($p < 0.05$).

Determination of the power-time relationship

There were no differences in parameter estimates derived from the three fitting models. This goodness-of-fit for both nonlinear and linear regressions was confirmed by $R^2$-values $> 0.98$. The 95% CIs associated with the estimated parameters of the power-time relationship were 2.7 to 5.1 W and 0.9 to 1.4 kJ for CP and $W'$, respectively. The CP was not significantly different between the HIGH and LOW groups. The CP relative to $P_{\text{max}}$ and $W'$ were significantly different between the HIGH and LOW groups ($p < 0.05$).
The actual $P_{\text{max}}$ for INC (317 ± 33 W; range = 217-383 W) was not significantly different from the predicted $P_{\text{max}}$ (320 ± 28 W; range = 240-371 W), and these values were highly correlated ($r = 0.94, p < 0.001$; see Fig. 1). The correlations between $P_{\text{max}}$ and $\text{VO}_{2\text{max}}$ ($r = 0.61$), $P_{\text{max}}$ and CP ($r = 0.89$) and between $P_{\text{max}}$ and $W'$ ($r = 0.55$) in the total sample were statistically significant ($p < 0.05$). A stepwise multiple regression analysis from the overall sample ($n = 30$) revealed that 80.7% of the variance for $P_{\text{max}}$ could be explained by CP alone ($F = 113.0, p < 0.001$), and the addition of $W'$ to the prediction equation increased it significantly (partial $F = 6.8, p < 0.01$) to 89.5% of the variance. Moreover, the difference between $P_{\text{max}}$ and CP was significantly correlated with $W'$ ($r = 0.73, p < 0.001$).

Discussion

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

The CP model has been applied to both constant-work rate exercise (CWR) and INC. Morton et al. (1997) have shown that CP and $W'$ estimated during INC...
were not different from those derived from conventional method (i.e., CWR). More recently, Chidnok et al. (2013) also found that CP model could accurately predict the performance (i.e., Tlim) during INC. In line with these studies, it was found that the actual $P_{max}$ for INC was not significantly different from predicted $P_{max}$ and they were highly correlated. Therefore, these results suggest some important applications. Firstly, it is possible to apply the CP model to estimate different parameters (e.g., Tlim, CP and $P_{max}$) during INC. Moreover, exercise in/tolerance during INC and CWR performed within severe-intensity domain seems to be determined by shared putative physiological mechanisms. Thus, these exercise protocols (INC and CWR) could provide similar insights into the nature of exercise intolerance in health and disease. Finally, CP was the best predictor of $P_{max}$. Interestingly, Greco et al. (2012) verified in untrained subjects that CP expressed as a unit of metabolic rate (i.e., VO$_2$) was highly correlated ($r = 0.98$) with VO$_{2max}$, suggesting that these variables could be determined by similar mechanisms. Thus, the different units utilized to express CP, $P_{max}$ and VO$_{2max}$, could explain the lower relationship between $P_{max}$ and VO$_{2max}$ observed in the present study. As mechanical variables, CP and $P_{max}$ are determined by metabolic rate and exercise economy, while VO$_{2max}$ expresses only the former.

Several variables (e.g., VO$_{2max}$, exercise economy and VO$_2$ kinetics) have been utilized to explain the inter-individual variability of $P_{max}$. However, the actual contribution for some of them is still obscure (e.g., anaerobic capacity and muscle power) (Jones and Carter 2000). There is a consensus that $P_{max}$ reflects the interaction between VO$_{2max}$ and exercise economy. However, some recent interventional studies have challenged the contribution of VO$_{2max}$ and exercise economy to explain the individual variability of $P_{max}$. In trained cyclists, Rønnestad
et al. (2014) have shown that $P_{\text{max}}$ was increased after a strength-training period, while both $VO_{2\text{max}}$ and gross efficiency were unchanged. In addition, Sawyer et al. (2014) found that $P_{\text{max}}$ (~ 8%), Tlim at severe-intensity domain (39%) and $W'$ (~ 40-60%) were improved after 8 weeks of strength training, whereas CP and $VO_{2\text{max}}$ were not significantly modified. Our data are in line with these studies, demonstrating that Tlim during severe-intensity exercise (CWR and INC) can be modified with no corresponding changes in aerobic parameters ($VO_{2\text{max}}$ and CP).

In these conditions, $W'$ is a determinant of Tlim, and consequently, $P_{\text{max}}$ 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 $VO_{2\text{max}}$) of the severe-intensity domain. However, the magnitude of $W'$ has also been associated with the accumulation of metabolites (i.e., [P] 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 $P_{\text{max}}$ reached during INC in physically active individuals with similar aerobic parameters (LT, CP and $VO_{2\text{max}}$). Moreover, the $P_{\text{max}}$ for INC can be predicted by CP model (i.e., CP and $W'$). Thus, the depletion of $W'$ and consequently the attainment of $VO_{2\text{max}}$ seems to influence the exercise tolerance during INC.
References


<table>
<thead>
<tr>
<th>Variables</th>
<th>Overall (N = 30)</th>
<th>HIGH (N = 10)</th>
<th>LOW (N = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{VO}_2\text{max}$ (L.min$^{-1}$)</td>
<td>3.58 ± 0.40</td>
<td>3.84 ± 0.50</td>
<td>3.49 ± 0.37</td>
</tr>
<tr>
<td>$P_{\text{max}}$ (W)</td>
<td>317 ± 33</td>
<td>337 ± 23</td>
<td>299 ± 40*</td>
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<tr>
<td>LT (W)</td>
<td>103 ± 26</td>
<td>92 ± 21</td>
<td>102 ± 17</td>
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<tr>
<td>CP (W)</td>
<td>206 ± 22</td>
<td>213 ± 22</td>
<td>200 ± 29</td>
</tr>
<tr>
<td>$\text{CP}/P_{\text{max}}$ (%)</td>
<td>65.0 ± 3.1</td>
<td>63.2 ± 3.8</td>
<td>66.8 ± 2.5*</td>
</tr>
<tr>
<td>$W'$ (kJ)</td>
<td>20.3 ± 4.3</td>
<td>25.1 ± 2.9</td>
<td>15.9 ± 1.8*</td>
</tr>
</tbody>
</table>

**HIGH**: high $W'$ group; **LOW**: low $W'$ group; **$\text{VO}_2\text{max}$**: maximal oxygen uptake; **$P_{\text{max}}$**: maximal power output; **LT**: lactate threshold; **CP**: critical power; **$\text{CP}/P_{\text{max}}$**: critical power relative to maximal power output; **$W'$**: curvature constant of the power-time relationship. * Significantly different between HIGH and LOW (p < 0.05).
FIGURE 1. Actual versus predicted maximal power output ($P_{\text{max}}$) during ramp incremental test. Prediction was made using parameters derived from the power-time relationship (i.e., CP and W’) (Morton 2011). The solid line is the best-fit linear regression, and the dashed line is the line of identity.
$r = 0.94$
$p < 0.001$
$N = 30$