Determination of Critical Power by Pulmonary Gas Exchange

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Catalogue Data

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Mots clés: cycle ergométrie, endurance, exercice

Abstract/Résumé

Although the physiological underpinnings of critical power (CP) have yet to be fully elucidated, it has been proposed that CP demarcates the heavy and severe exercise intensity domains and that each domain is associated with a different pattern of metabolic response and mechanism of fatigue. Severe intensity has been defined such that, during exercise at intensities above CP, the slow component of the VO₂ response will drive VO₂ to VO₂max at the point of fatigue. In this study, two parameters were derived for each of 8 participants: (a) CP, the asymptote of the relationship between power and time to exhaustion, and (b) a related parameter, CP′, the asymptote of the relationship between power and time to VO₂max. CP′ theoretically represents the threshold intensity above which VO₂max will be elicited during exercise of sufficient duration. Participants performed two exhaustive tests at CP. There were three important findings: First, there was a practice effect on time to exhaustion at CP, and times increased 27% in the second test. Second, both CP and CP′ could be obtained with good precision. Third, and most important, CP was equal to CP′, thereby providing a physiological description of the mathematically derived CP parameter. It was concluded that VO₂max cannot be elicited at intensities equal to or less than CP.

Les bases physiologiques de la puissance critique (PC) ne sont pas encore connues. Poole et collègues (1988, 1990) ont déjà suggéré que la PC est la ligne de démarcation entre les

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domaines d'intensité sévère et lourd et que, pendant l'exercice dans le domaine sévère, à cause de la deuxième partie de la réponse du $\text{VO}_2\text{max}$ et du $\text{VO}_2$, augmente jusqu'au $\text{VO}_2\text{max}$ au moment d'épuisement. Cet étude a calculé deux paramètres pour chacun de huit sujets: (a) $\text{PC}$, l'asymptote de la relation entre la puissance et le temps-limité, et (b) $\text{PC}'$, l'asymptote de la relation entre la puissance et le temps-à-$\text{VO}_2\text{max}$. En théorie, la $\text{PC}'$ est l'intensité au-dessus de laquelle on arrivera à $\text{VO}_2\text{max}$ si la durée est suffisante. Les sujets ont fait deux tests à $\text{PC}$. Nous avons trouvé trois choses importantes: D'abord, il y avait un effet d'habituation, et les temps-limités étaient plus longues dans le deuxième test. Deuxième, les deux paramètres, $\text{PC}$ et $\text{PC}'$, les deux pourraient être calculées avec de bonne précision. Troisième, et la plus importante, $\text{PC}$ était égale à $\text{PC}'$. Alors, voici une base physiologique pour la $\text{PC}$. La conclusion est que le $\text{VO}_2\text{max}$ ne peut pas être obtenu pendant l'exercice aux intensités égales à, ou au moins de, la $\text{PC}$.

**Introduction**

The hyperbolic relationship between exercise intensity and time to exhaustion is the basis of the critical power concept (Hill, 1993; Monod and Scherrer, 1965; Moritani et al., 1981). Time to exhaustion is a function of anaerobic work capacity (AWC) and critical power (CP). The relationship is:

\[
\text{time to exhaustion} = \text{AWC} \cdot (\text{power} - \text{CP})^{-1}
\]  

(1)

CP has been shown to be related to other indices of aerobic fitness such as ventilatory threshold, lactate threshold, or $\text{VO}_2\text{max}$ (Housh et al., 1991; McLellan and Cheung, 1992; Moritani et al., 1981), and to performance in long-duration events (Jenkins and Quigley, 1992; Kranenburg and Smith, 1994; Wakayoshi et al., 1992; Zaryski et al., 1994). However, there is little information on the physiological underpinnings of CP. Only Poole and colleagues (1988, 1990) have attempted to elucidate a physiological basis, and their hypothesis has been clearly presented in a recent review (Gaesser and Poole, 1996). They have proposed that, during prolonged exercise at intensities above CP, the slow component of the $\text{VO}_2$ response will drive $\text{VO}_2$, not to a delayed steady state but to $\text{VO}_2\text{max}$ at the point of fatigue.

Given that the kinetics of the $\text{VO}_2$ response are a function of intensity and that $\text{VO}_2\text{max}$ can be elicited at a variety of intensities (Gaesser and Poole, 1996), it has been hypothesized that, just as the relationship between intensity and time to exhaustion can be fitted to the hyperbolic model, so could the relationship between intensity and time to achieve $\text{VO}_2\text{max}$ (Rowell et al., 1996). The relationship is:

\[
\text{time to } \text{VO}_2\text{max} = \text{AWC}' \cdot (\text{power} - \text{CP}')^{-1}
\]  

(2)

Rowell et al. stated that $\text{CP}'$ should represent the highest intensity that could be sustained without $\text{VO}_2\text{max}$ being elicited, and that $\text{AWC}'$ should represent the amount of work performed anaerobically before $\text{VO}_2\text{max}$ was attained. They found that $\text{CP}$ and $\text{CP}'$ were not different (since they were using treadmill running rather than cycle ergometry, these two parameters were expressed as velocities, 242 ± 26 and 242 ± 28 m · min⁻¹, respectively), and they concluded that $\text{CP}$ defines the threshold intensity above which exercise of sufficient duration would elicit $\text{VO}_2\text{max}$. 
The present study had three purposes: (a) to determine how long individuals could exercise at CP when allowed two attempts and when not given any cutoff time (i.e., when directed to exercise for as long as possible); (b) to evaluate the relationship between intensity and time to achieve O₂max in cycle ergometer exercise; and (c) to compare CP and CP'. The hypotheses were: (a) there would be a practice effect on time to exhaustion at CP; (b) the relationship between intensity and time to achieve O₂max could be described by a hyperbolic model (Equation 2); and (c) CP and CP' would be the same.

Methods

Six women and 2 men volunteered to participate in the study, which had been previously approved by the institutional review board at the University of North Texas. Their age, height, and weight are listed in Table 1. All participants were involved in recreational activities, but none was training for any athletic contests.

Each participant underwent 10 exhaustive cycle ergometer tests, all on the same electronically braked cycle ergometer (Minjhart 800S, The Netherlands) and all at the same time of day under similar conditions in a climate-controlled laboratory (20 to 22 °C). The first five high-intensity tests were each undertaken on a separate day and each at a different power output. Then, beginning 1 or 2 days

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Mean ± SD

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Note. Times are reported to nearest 0.1 min.
later, each participant repeated tests at the three work rates that had produced the longest times to exhaustion. Because we have previously reported a small learning effect in estimates of CP generated after the performance of 5 practice trials (Smith and Hill, 1993), only the results of the final 3 predicting trials were used in the estimation of CP and CP'. Finally, each participant twice exercised to exhaustion at CP.

CONSTANT POWER TESTS

Power outputs for four of the first five high-intensity tests were preselected based on body weight. For the women these were 3.5, 4.5, 5.5, and 6.5 W · kg⁻¹. For the men these were 4.0, 5.5, 7.0, and 8.5 W · kg⁻¹. The power for the fifth test was selected based on responses to the first four. In most cases the fifth power output was lower than the other four and provided an exercise time that was longer than that achieved during exercise at the standard loads. Tests at the two highest power outputs resulted in times to exhaustion that averaged less than 1 min. It has been recommended that durations used to calculate CP be between 1 and 10 min (Poole, 1986). Therefore, participants repeated tests using only the three lowest power outputs. None of these three tests lasted less than 1 min, and each participant had one test that lasted over 5 min.

Each test was preceded by a 5-min warm-up at a power output that was individually adjusted to elicit a heart rate between 120 and 130 bpm. This was followed by 5 min of seated rest on the ergometer. Then participants accelerated against zero resistance until they reached 100 rpm and the resistance was imposed (power output achieved in 1 to 3 sec). Pedal cadence was at the participants' discretion, since power output on this ergometer is independent of pedal cadence. This methodology was recently shown to be superior to using tests requiring fixed pedal cadences to determine CP (Hill et al., 1995).

A test was terminated when the participant could not sustain a cadence above 50 rpm despite verbal encouragement. If the cadence fell below 50 rpm for less than 3 sec but the participant was able to regain the required pedal cadence, the test continued. Typically there was a precipitous end to each exercise bout.

During each exercise test, expired gases were collected and analyzed using a MedGraphics (St. Paul, MN) metabolic cart. The cart was calibrated before each test according to manufacturer instructions using 12% O₂ and 5% CO₂ gases and a 3-L syringe, all provided and guaranteed by the manufacturer. Calibration was verified after the tests. Time to exhaustion was measured to the nearest second, and VO₂max for that test was determined as the highest 30-sec average determined from rolling averages of 15-sec means. The time to achieve VO₂max was determined as the time from onset of exercise until the middle of the first 15-sec window when the 15-sec value for VO₂ reached or exceeded the 30-sec value for VO₂max achieved in that test. Because the mode of exercise was cycling, the VO₂max represents a mode-specific maximum. For this reason, readers may prefer to think of it as a peak value. It can be argued that the peak value obtained in an exhaustive test of 1 to 10 min duration does in fact represent a mode-specific VO₂max (e.g., Åstrand and Saltin, 1961; Gaesser and Poole, 1996). During the tests, the participants were not given any information about their elapsed time. They were also not informed of the test duration or any other physiological responses until they were debriefed after all the data had been collected.
DETERMINATION OF CP AND AWC

Estimates of AWC and CP were generated using three different forms of the power–time relationship. The three models are mathematically equivalent forms of the hyperbolic function:

\[
\text{time to exhaustion} = \text{AWC} \cdot (\text{power} - \text{CP})^{-1}
\]  
(1)

and may be written as two linear relationships:

\[
\text{power} = (\text{AWC} \cdot \text{time}^{-1}) + \text{CP}
\]  
(3)

and

\[
\text{work} = (\text{CP} \cdot \text{time}) + \text{AWC}
\]  
(4)

Parameters were derived for the nonlinear power–time model using iterative nonlinear regression, and for the linear power–time\(^{-1}\) and linear work–time relationships using linear regression, all on SPSS. The CP values obtained using the three models were compared in order to evaluate the accuracy of the parameter estimates (Hill and Smith, 1994). For each participant, the parameter estimate generated using the nonlinear model was recorded as the criterion measure of CP. This model was selected to be used for determining the criterion value because it properly sets power as the independent variable and time to exhaustion as the dependent variable (Gaesser et al., 1995).

DETERMINATION OF CP' AND AWC'

The power and the time to achieve \(\dot{\text{V}}\text{O}_2\text{max}\) were fit to three models similar to those described above. There were a hyperbolic model:

\[
\text{time to } \dot{\text{V}}\text{O}_2\text{max} = \text{AWC'} \cdot (\text{power} - \text{CP'})^{-1}
\]  
(2)

and two linear models:

\[
\text{power} = (\text{AWC'} \cdot \text{time}^{-1}) + \text{CP'}
\]  
(5)

and

\[
\text{work} = (\text{CP'} \cdot \text{time}) + \text{AWC'}
\]  
(6)

The criterion measure for CP' was the value derived using the nonlinear model.

TESTS AT CP

Participants completed two exercise tests at CP separated by at least 48 hrs. Specifically, for two participants the delay was 2 days, for two others it was 3 days, and for the other four participants the tests were separated by exactly 1 week. Although CP was calculated to the nearest 1 W, the work rate on the ergometer could be set only in multiples of 5 W. Therefore, actual powers used in the tests may not have been exactly CP (the average difference was under 2 W).

During these tests the participants were encouraged to make all-out efforts. They were cooled with fans and were given water (only) to drink, their choice of loud music, and strong verbal encouragement. For five of the eight participants,
pedal cadence was monitored at 5-min intervals during the tests, and the average value for the first 60% of each test was determined as their chosen cadence. As in the high-intensity tests, the participants were not apprised of elapsed time during any trial, and they did not know the results of their first trial when they undertook the second trial.

STATISTICAL ANALYSES

The values for \( \dot{V}O_2 \text{max} \) determined in the long, medium, and short predicting trials were compared using a repeated measures ANOVA. To evaluate the physiological significance of CP, CP was compared with CP' using a paired-means t-test and a Pearson product moment correlation. In addition, the times to exhaustion in the two tests at CP were compared using a paired-means t-test and a Pearson product moment correlation. Statistical significance was preset at an alpha of ≤0.05.

| Table 2 | The 8 Individuals’ Values for CP and CP’ (units in watts) and Associated SEE and R², Derived from 3 Mathematical Models |
|----------------|-------------------------------------------------|----------------|-----------------|-----------------|----------------|
| Subj. | Power—time | Work—time | Power—time—1 | CV |
| CP ± SEE (R²) | | | | |
| 1 (f) | 177 ± 0 (1.000) | 176 ± 1 (1.000) | 175 ± 4 (0.999) | 1% |
| 2 (m) | 272 ± 2 (1.000) | 274 ± 4 (1.000) | 283 ± 15 (0.991) | 2% |
| 3 (m) | 169 ± 2 (0.999) | 167 ± 4 (0.999) | 160 ± 14 (0.987) | 3% |
| 4 (f) | 143 ± 5 (0.993) | 140 ± 9 (0.996) | 134 ± 23 (0.942) | 3% |
| 5 (f) | 167 ± 9 (0.981) | 176 ± 10 (0.997) | 184 ± 10 (0.977) | 5% |
| 6 (f) | 143 ± 11 (0.978) | 153 ± 11 (0.995) | 161 ± 10 (0.980) | 6% |
| 7 (f) | 133 ± 6 (0.993) | 129 ± 9 (0.995) | 122 ± 19 (0.967) | 4% |
| 8 (f) | 151 ± 2 (0.999) | 150 ± 3 (1.000) | 147 ± 5 (0.998) | 1% |
| Means: | 170 ± 44 | 171 ± 45 | 171 ± 50 | 3 ± 2 |
| CP = | 5 ± 4 | 6 ± 4 | 13 ± 7 | |
| SEE = | 0.993 ± 0.0009 | 0.998 ± 0.002 | 0.980 ± 0.019 | |
| R² = | | | | |
| CP’ ± SEE (R²): | | | | |
| 1 (f) | 163 ± 4 (0.998) | 165 ± 6 (0.999) | 176 ± 16 (0.979) | 4% |
| 2 (m) | 263 ± 4 (0.999) | 266 ± 6 (0.999) | 278 ± 20 (0.986) | 3% |
| 3 (m) | 161 ± 5 (0.996) | 157 ± 8 (0.997) | 147 ± 24 (0.969) | 5% |
| 4 (f) | 170 ± 18 (0.569) | 142 ± 9 (0.996) | 136 ± 25 (0.931) | 12% |
| 5 (f) | 158 ± 15 (0.961) | 172 ± 15 (0.993) | 181 ± 12 (0.968) | 7% |
| 6 (f) | 134 ± 22 (0.940) | 153 ± 19 (0.985) | 162 ± 14 (0.962) | 10% |
| 7 (f) | 140 ± 3 (0.996) | 138 ± 6 (0.998) | 131 ± 14 (0.772) | 3% |
| 8 (f) | 150 ± 1 (1.000) | 151 ± 2 (1.000) | 152 ± 3 (0.999) | 1% |
| CP' = | 167 ± 40 | 168 ± 41 | 171 ± 47 | 6 ± 4 |
| SEE = | 0 ± 8 | 9 ± 6 | 15 ± 6 | |
| R² = | 0.932 ± 0.148 | 0.996 ± 0.005 | 0.946 ± 0.073 | |

**Note.** Criterion measures were the values obtained using the nonlinear power—time model, Equations 1 and 4.
Results

The mean (±SD) power outputs for the predicting trials were 328 ± 86, 256 ± 70, and 198 ± 43 W. Times to exhaustion were 85 ± 11, 171 ± 68, and 522 ± 189 sec. Times to achieve VO\textsubscript{max} were 67 ± 15, 140 ± 69, and 352 ± 94 sec.

Individual values for CP derived via the three mathematical models (i.e., Equations 1, 3, and 4), and for the SEE and R\textsuperscript{2} associated with each parameter estimate, are presented in Table 2. The mean value for CP (using the nonlinear model, Equation 1) was 170 ± 44 W. Actually, the relationship between power and time to exhaustion was well described by all three mathematical forms of the hyperbolic model (Equations 1, 3, and 4). For each model, the mean R\textsuperscript{2} was ≥0.980 and the mean SEE was ≤13 W (7% of the mean). The mean CP values obtained via the three mathematically equivalent models were 170, 171, and 171 W.

The individual times to exhaustion during the two tests at CP are presented in Table 1. Times increased 27% (t = 2.78, p = 0.03) from 51.3 ± 13.2 min in the first test to 65.0 ± 10.6 min in the second. The correlation between the times to exhaustion in the first and second attempt at CP was 0.33 (p = 0.42).

Results of the repeated measures ANOVA revealed that the mean values for VO\textsubscript{max} determined in the long, medium, and short predicting trials were not different. The overall mean was 2.62 L min\textsuperscript{-1} (41.7 ml kg\textsuperscript{-1} min\textsuperscript{-1}). Individual data are presented in Table 3. Gas exchange data from the three predicting trials for a representative participant are shown in Figure 1.

It was possible to mathematically describe the relationship between power and time to attain VO\textsubscript{max}, and thus to derive estimates of CP'. Individual values for CP' derived via the three mathematical models (Equations 2, 5, and 6) and for the SEE and R\textsuperscript{2} associated with each parameter estimate, are presented in Table 2.

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<tr>
<th>Table 3</th>
<th>Individual Values for VO\textsubscript{max} During the 3 Predicting Trials</th>
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<td>Mean ±SD</td>
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</table>

Note. Mean values presented in Results section.
The mean value for CP′ using the nonlinear model (Equation 2) was 167 ± 40 W. Actually the relationship between power and time to attain VO\textsubscript{max} was quite well described by all three mathematical forms of the hyperbolic model (Equations 2, 5, and 6). For each model, the mean $R^2$ was ≥0.932 and the mean SEE was ≤15 W (9% of the mean). The mean values obtained using the three models were 167, 168, and 171 W. The relationships between power and time to exhaustion and between power and time to achieve VO\textsubscript{max} for a representative participant are shown in Figure 2.

CP and CP′ were not statistically different ($t = 0.45, p = 0.67$). The two values were highly correlated ($r = 0.95, p < 0.01$).

Assuming that the slope of the watts : VO\textsubscript{2} relationship was midway between 10 ml · min\textsuperscript{-1} · W\textsuperscript{-1} (Hansen et al., 1988) and 12 ml · min\textsuperscript{-1} · W\textsuperscript{-1} (American College of Sports Medicine, 1995), and that the participants' resting VO\textsubscript{2} was 3.5 or 220 ml · min\textsuperscript{-1} (ACSM, 1995), the VO\textsubscript{2} associated with CP was calculated to be approximately 2.09 L · min\textsuperscript{-1} or 80% of VO\textsubscript{max}.

**Discussion**

As expected, the relationship between power and time to exhaustion was well described by the three forms of the hyperbolic model (Equations 1, 3, and 4). The high $R^2$, the low SEE, and the similarity of values obtained using the three models suggested that valid estimates were obtained (Hill and Smith, 1994). The values
for $SEE$ and $R^2$ were similar to those previously reported for the power–time relationship (Housh et al., 1989, 1991; Jenkins and Quigley, 1990, 1992; McLellan and Cheung, 1992; Poole et al., 1988, 1990).

Even after several exhaustive high-intensity exercise tests were performed, time to exhaustion at CP was subject to a considerable practice effect (+27%). CP was associated with an $O_2$ demand of ~80% $\dot{VO}_2$ max. McLellan et al. (1995) recently reported considerable intraindividual variability in time to exhaustion during five cycling trials at 80% $\dot{VO}_2$ max and an improvement in later trials.

One possible reason for the improved performance in the second trial could be glycogen supercompensation consequent to the first trial. We have no data to test the possibility that there was a glycogen supercompensation in response to the first, depleting bout. We did not monitor diet. Participants 1 and 3 were retested after 2 days and had improved 15.0 and 21.2 min. Participants 5 and 8 were retested after 3 days and had improved 4.8 and 7.3 min. The other four participants, who had 1 week between tests, improved the most (35.0 and 29.5 min) and least (1.0 and 4.2 min). Thus, no consistent effect of the different recovery periods and/or the potential role of glycogen supercompensation can be inferred from these data.

Time to exhaustion in the second trial at CP was 65 min. Previous studies have reported shorter times to exhaustion at CP (Housh et al., 1989; Jenkins and Quigley, 1990; McLellan and Cheung, 1992; Scarborough et al., 1991). Three factors may account for the longer times in the present study: First, participants were directed to exercise for as long as possible. In other studies, whether explicitly stated or simply implied, there was a target of 24 to 90 min, and time to exhaustion may have been biased by expectations of the participants.

Second, participants were permitted to choose and to vary their cadence. Variable cadence methods have been used by Overend et al. (1992) and McLellan...
and Cheung (1992), and this methodology has been shown to be superior to fixed-pedal cadences for determining CP (Hill et al., 1995). We note that the choice of cadence during the tests at CP differed among participants and often was not what we would have suggested. For example, one individual maintained ~108 rpm before beginning to fatigue, while two others chose ~65 rpm. The pedal cadence data in Table 1 suggests that, in and of itself, mean pedal cadence did not appear to be related to performance, and that individual changes in performance at CP were not associated with changes in cadence.

Third, participants were allowed a second attempt at CP and they appeared to benefit from the practice. Scarborough et al. (1991) reported that time to exhaustion increased from 43 min to 51 min from the first to second trial at CP. McLellan and Cheung (1992) found no improvement in a second trial undertaken by 9 men. However, the conditions for the two trials differed in terms of the use of handlebars and type of warm-up, so it was not possible to directly assess reproducibility. In the present study, performance in the first trial generally underestimated, and was not a good predictor of, subsequent performance, although the test-retest correlation of only 0.33 might in part be attributed to the small sample size. Since we did not have our participants perform a third effort at CP, we cannot conclude that a true time to exhaustion was determined. However, it does seem clear that a true time to exhaustion is not obtained with only one trial.

To date, CP has been determined, defined, and described based purely on statistical evaluation of the power–time relationship, and only one group of investigators has attempted to provide a physiological basis for CP. Poole et al. (1988, 1990) hypothesized that CP, which was derived using the linear power–time model described by Equation 3, represented the threshold intensity above which VO2 would gradually increase to VO2,max.

Clearly, VO2,max can be elicited during constant power exercise at a range of intensities (Gaesser and Poole, 1996). Evidence that VO2 will increase to VO2,max only during exercise above CP was provided by Poole et al. (1988, 1990), who showed that, during exercise at CP, VO2 reached a steady state at ~75% of VO2,max. But during exhaustive exercise at power outputs averaging about 8 to 11% (16 to 23 W) above CP—and only 74 to 78% of the work rate associated with attainment of VO2,max in an incremental test—VO2 reached 95 to 97% of VO2,max. Poole et al. concluded that VO2,max would not be elicited by exercise at CP, but that it would be elicited by exercise at an intensity that was slightly (i.e., 8 to 11%) above CP.

If the hypothesis of Poole et al. (1988, 1990) is correct, VO2,max should be achieved during exercise at intensities that are as little as 1 W or even less above CP. Poole et al. tested responses to exercise at intensities averaging 16 or 23 W above CP. How small an increment above CP is required before VO2,max will eventually be reached is a difficult question to answer because of day-to-day variations in both time to exhaustion and VO2,max. In addition, the precision with which CP is estimated or work rates can be set on an ergometer is certainly not as little as 1 W or less.

Finally, methodological considerations can affect estimates of CP. For example, in Hill et al. (1995), the mean CP for 24 participants was estimated to be 203 W using the variable cadence regimen and hyperbolic model (Equation 1) employed in the present study. In contrast, using the fixed 60-rpm cadence and the
linear power–time\textsuperscript{-1} model used in the Poole et al. (1988, 1990) studies, the mean CP for these same individuals was 212 W. Probably, when one tests responses at CP \textpm 20 W, one can be sure the participants are indeed exercising above their CP. However, future studies should be designed to estimate CP as precisely as possible and perhaps test responses at intensities only slightly above and below CP.

In the present study, within the range of power outputs used to calculate CP, there was also a relationship between power output and the time needed to achieve VO\textsubscript{2}max. This relationship was well described by three forms of a hyperbolic model, Equations 2, 5, and 6. The mean values for CP' obtained using the three mathematically equivalent models were 167, 168, and 171 W. Considering the relatively low SEE and the high \( R^2 \) for each model for most participants, and the agreement between estimates generated by the three different models, it was concluded that the relationship between power and time to achieve VO\textsubscript{2}max could be described by a hyperbolic model, and the two mathematically equivalent linear forms of the relationship.

CP', which theoretically represents the highest power that will not elicit VO\textsubscript{2}max, was found to equal CP. Thus the results of the present study indirectly support the hypothesis of Poole et al. (1988, 1990) that, during exercise at an intensity above CP, VO\textsubscript{2} will gradually increase to VO\textsubscript{2}max. Similar support for this hypothesis was provided by Rowell et al. (1996), who used running exercise rather than cycle ergometry. It must be acknowledged that, while the two sets of values obtained in the present study were highly correlated (\( r = 0.95 \)) and not significantly different (\( p = 0.67 \)), the difference between individual values was as great as 27 W; for some participants the CP estimate was greater than the CP', while for others the opposite was true. One can speculate that using even more trials to calculate CP' might have reduced these differences since, regardless of the mathematical model used, the CP estimates were associated with smaller SEE and larger \( R^2 \) than the CP' estimates.

In summary, CP is easily obtained without expensive equipment, invasive measures, or sophisticated techniques. As it is a valid index of aerobic function, it is a meaningful parameter, but one for which the physiological underpinnings have yet to be elucidated. There were two important findings in this study regarding the practical significance of CP: (a) There is a practice effect in performance at CP even when that test is preceded by a number of all-out high-intensity tests. (b) After a practice trial, mean time to exhaustion is about 1 hour. This is the only published study in which participants were provided two opportunities and were directed to exercise for as long as possible at CP with no predetermined cutoff time.

Poole et al. (1988, 1990) and Gaesser and Poole (1996) have concluded that CP is the highest power at which VO\textsubscript{2}, and other metabolic indices such as blood lactate concentration, lactate-to-pyruvate ratio, bicarbonate concentration, and blood pH can achieve a steady state. They have concluded that, as such, CP should represent an "upper limit for sustainable power" (Poole et al., 1990, p. 421). In this study, we calculated CP and a second parameter, CP', which theoretically represents the threshold intensity above which exercise of sufficient duration will lead to attainment of VO\textsubscript{2}max. CP and CP' were determined with good precision, as reflected by the low SEE, high \( R^2 \), and low variability in estimates obtained using the three mathematical models. CP was equal to CP'. Thus we have provided strong
evidence to support the contention of Poole et al. (1988, 1990) that CP can be described in physiological terms as the threshold power above which VO₂max can be elicited.

References


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