Human critical power–oxygen uptake relationship at different pedalling frequencies

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Critical power (CP) is lower at faster rather than slower pedalling frequencies and traditionally reported in watts (W). Faster pedalling frequencies also engender a greater metabolic rate ($\dot{V}O_2$) at low work rates, but with progressive increases in power output, the initial difference in $\dot{V}O_2$ between fast and slower pedalling frequencies is reduced. We tested the hypothesis that CP represents a unique metabolic rate for any given individual which would be similar at different pedalling frequencies. Eleven collegiate athletes (five cross-country runners, END; six sprinters, SPR), aged 18–23 years, performed exhaustive rides at either 60 or 100 r.p.m. on separate days for the determination of the pedal rate-specific CP. The $\dot{V}O_2$ at CP (CP-$\dot{V}O_2$) was determined from an 8 min ride at the CP for each pedal frequency. The group mean CP was significantly lower at 100 r.p.m. (189 ± 50 W) compared to 60 r.p.m. (207 ± 53 W, P < 0.05). However, the group mean CP-$\dot{V}O_2$ values at 60 (2.53 ± 0.60 l min$^{-1}$) and 100 r.p.m. (2.58 ± 0.53 l min$^{-1}$) were not significantly different. Critical power was significantly higher in the END athletes (242 ± 50 W at 60 r.p.m.; 221 ± 56 W at 100 r.p.m.) compared to SPR athletes at both pedal frequencies (177 ± 38 W at 60 r.p.m.; 162 ± 27 W at 100 r.p.m., P < 0.05), but the CP-$\dot{V}O_2$ was not (P > 0.05). However, when the CP-$\dot{V}O_2$ was scaled to body weight, the END athletes had a significantly greater CP-$\dot{V}O_2$ (41.3 ± 4.1 ml min$^{-1}$ kg$^{-1}$ at 60 r.p.m.; 40.8 ± 5.5 ml min$^{-1}$ kg$^{-1}$ at 100 r.p.m.) compared to the SPR athletes at both pedal frequencies (27.7 ± 4.6 ml min$^{-1}$ kg$^{-1}$ at 60 r.p.m.; 29.4 ± 2.8 ml min$^{-1}$ kg$^{-1}$ at 100 r.p.m., P < 0.05). We conclude that CP represents a specific metabolic rate ($\dot{V}O_2$) which can be achieved at different combinations of power outputs and pedalling frequencies.

(Received 15 November 2005; accepted after revision 6 March 2006; first published online 9 March 2006)

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The hyperbolic relationship between power output and the time over which this power can be sustained (time to fatigue, or endurance) was originally introduced by Hill (1927). From this hyperbolic relationship there is an upper limit of constant power output that can theoretically be maintained indefinitely (i.e. without exhaustion), relying on renewable aerobic energy supply, which has been termed the power asymptote of critical power (CP; Monod & Scherrer, 1965). The power asymptote of critical power has been shown to lie above the traditional ‘anaerobic’ or lactate threshold (Monod & Scherrer, 1965; Poole et al. 1988, 1990; Carnevale & Gaesser, 1991). The power–endurance hyperbolic relationship may also be fitted to a linear function using the reciprocal of time to fatigue. In this case, CP is graphically represented by extrapolation to the y-intercept. The slope of the linear, and degree of curvature in the hyperbolic, power verus time-to-fatigue relationships represent the so-called anaerobic work capacity (AWC). The AWC represents a finite quantity of work that can be performed above CP, presumably using energy derived from anaerobic glycogenolysis, phosphagen and oxygen stores (Monod & Scherrer, 1965; Moritani et al. 1992 1965 Miura et al. 1999, 2000). Thus, CP and the AWC establish two components that define the power–endurance (i.e. time-to-fatigue) relationship.

Factors that are temporally and possible mechanistically associated with fatigue (such as blood lactate,
lactate-to-pyruvate ratio, bicarbonate concentration and [H+] have been shown to reach a steady state during exercise above the lactate threshold but below or at CP (Poole et al. 1988, 1990). Thus, CP may be considered as the maximal external work rate (W), which can be sustained for prolonged exercise durations where the above-listed factors can be stabilized (Smith et al. 1999). However, during cycle exercise above CP, oxygen consumption (VO2) and blood lactate concentrations continue to rise until exhaustion ensues or exercise is terminated (Hill et al. 2002; Poole et al. 1988, 1990; Whipp & Ward, 1990; Smith & Jones, 2001). Thus, CP provides a marker for the separation of exercise intensity domains into heavy (below CP) and severe (above CP) based upon the physiological responses (Whipp & Wasserman, 1972; Whipp & Ward, 1990).

The manipulation of pedalling frequency directly affects the shortening velocity (Soest & Casius, 2000) and recruitment of different muscle fibres (Ahlquist et al. 1992). For the same external W, slow pedalling frequencies require greater force production per pedal thrust, whereas faster pedalling frequencies require a faster contraction velocity (Sjogaard, 1978), both of which have been shown to recruit fast-twitch muscle fibres (Ahlquist et al. 1992). Fatigue occurring at a slower pedalling frequency at high power outputs results in the precipitous decline in pedalling frequency resulting from both fatigue of some of the recruited motor units and the simultaneous increase in resistance (torque) on the cycle ergometer to maintain that same power output as the pedalling rate slows. In contrast, the inability to maintain faster pedalling frequencies may be the result of selective fatigue of some of the initially recruited fast-twitch fibres, as evidenced by the ability to continue cycling at a slower pedalling frequency (Beelen & Sargeant, 1991; Sargeant, 1994). Previous research has demonstrated that CP is lower, on average, at a faster pedalling frequency resulting from both fatigue of some of the recruited motor units and the simultaneous increase in resistance (torque) on the cycle ergometer to maintain that same power output as the pedalling rate slows. In contrast, the inability to maintain faster pedalling frequencies may be the result of selective fatigue of some of the initially recruited fast-twitch fibres, as evidenced by the ability to continue cycling at a slower pedalling frequency (Beelen & Sargeant, 1991; Sargeant, 1994). Previous research has demonstrated that CP is lower, on average, at a faster pedalling frequency (i.e. 90–110 r.p.m.) when compared to a slower pedalling frequency (i.e. 50–70 r.p.m.), while the AWC has been shown to be either unaffected (Carnevale & Gaesser, 1991; Hill et al. 1995; McNaughton & Thomas, 1996) or higher at slower pedalling frequencies (e.g. 50–60 r.p.m.; Green et al. 1995). However, in these previous studies comparing CP and AWC at different pedalling frequencies there was no assessment of the underlying muscle fibres nor consideration of any effect of fibre types (i.e. fast versus slow).

Previous research has demonstrated that at low external power outputs (i.e. < 50 W) there is a greater metabolic response (higher VO2) at a faster pedalling frequency (100–105 r.p.m.) when compared to slower pedalling frequencies (40–60 r.p.m.; Suzuki, 1979; Carnevale & Gaesser, 1991; Takaishi et al. 1994, 1996, 1998; Francescato et al. 1995; Zoladz et al. 1995; Brisswalter et al. 1999). However, as greater power outputs are imposed (e.g. incremental ramp test) the initial difference in VO2 is reduced as the VO2-power output relationships converge, so that peak VO2 and peak work rates are similar at different pedal frequencies (Zoladz et al. 2000).

The primary purpose of this study was to determine whether the disparate power outputs representing CP at 100 and 60 r.p.m. elicit similar VO2 responses independent of pedalling frequency. A second purpose was to assess whether these responses to different pedalling rates would be different in highly trained track athletes that theoretically possess either high (endurance, END) or low percentages (sprinter, SPR) of type I muscle fibres. Specifically, we tested the hypotheses that: (1) the CP would be less, but the VO2 at CP would be the same, at 100 compared to 60 r.p.m.; and (2) SPR athletes would have lower CP, but greater AWC, than END athletes.

**Methods**

**Subjects**

The present study consisted of two groups of subjects: (1) cross-country runners (END, n = 5, all male); and (2) sprinters (SPR, n = 6, one female). Subjects were characterized as END or SPR if they competed on the cross-country team or sprinted the 100 m events, respectively. Subjects were currently or had recently competed at the Division I collegiate level. Subjects were informed of the experimental protocol and provided written and verbal consent prior to enrolment. The study was approved by the Human Subjects Committee at Kansas State University and conformed to the Declaration of Helsinki.

**Exercise protocol**

Subjects reported to the Human Exercise Physiology Laboratory at Kansas State University on 11 separate occasions. Testing sessions were performed prior to any competitive training for that particular day, separated by at least 48 h, and performed at the same time of day for a given subject. The handlebars, seat height, and toeclips were adjusted during their initial visit for comfort, and were standardized and reproduced in their following visits. Initially, each subject performed two incremental ramp tests to volitional fatigue, the first at 60 r.p.m. and the second at 100 r.p.m., on separate occasions to determine peak VO2 (VO2Peak), peak work rate (WPeak) and gas exchange threshold (GET) for each pedal frequency. Each ramp test consisted of 4 min of unloaded cycling, followed by an incremental (ramp) increase in power output to volitional fatigue on an electromagnetically braked cycle ergometer (Lode Corival model 844, Corival, Lode BV, Groningen, Netherlands). The rate of increase in power output ranged between 20 and 30 W min−1 based on the subject’s individual fitness, and was the same for both 60 and 100 r.p.m. tests.
Critical power–oxygen uptake relationship

For the following eight visits, each subject performed exercise to exhaustion at the workloads representing 110, 100, 90 and 85% of the pedal rate-specific \( W_{\text{Peak}} \) obtained during their respective ramp tests. These workloads were chosen to elicit exhaustion in approximately 2–15 min. The rationale for this specific order was to allow subjects to experience the fatiguing process at the higher work rates at both pedalling frequencies first, where motivation was thought to play less of a role in performance. Each subject performed the four separate workloads at 60 and 100 r.p.m., respectively. One END-trained subject was only able to complete three of the four exhaustive rides at each pedal frequency due to re-occurring headaches. During testing sessions subjects were not informed of the imposed workloads or their performance times. The time to fatigue was taken as the elapsed time, in seconds, between the imposed exhaustive workload and the time at which the subject could no longer maintain at least 95 r.p.m. for the 100 r.p.m. trials and 55 r.p.m. for the 60 r.p.m. trials, despite strong verbal encouragement.

Following completion of the previously mentioned eight trials, subjects returned to the laboratory for their last visit, which consisted of two separate rides at their pedal rate-specific CP values (CP
\(_{\text{ind}}\)). Each ride sequentially consisted of cycling for 4 min at 30 W, 8 min at the pedal rate-specific CP, and 8 min at 30 W. The order of pedal frequency was randomly selected, and the exercise bouts were separated by 60 min of rest.

**Data analysis**

Pulmonary gas exchange (\( V_O_2 \) and carbon dioxide production, \( V_{CO_2} \)) and minute expired ventilation (\( V_E \)) were measured breath by breath using a metabolic measurement system (Cardio2, Medical Graphics Corp., St Paul, MN, USA). The system was calibrated prior to each

### Table 1. Incremental ramp data

<table>
<thead>
<tr>
<th></th>
<th>GET–( V_O_2 ) (ml kg (^{-1} ) min (^{-1} ))</th>
<th>GET–( V_O_2 ) (W)</th>
<th>( W_{\text{GET}} ) (W)</th>
<th>( W_{\text{Peak}} ) (W)</th>
<th>( V_{O_2\text{Peak}} ) (ml kg (^{-1} ) min (^{-1} ))</th>
<th>( S_1 ) (ml min (^{-1} ) W (^{-1} ))</th>
<th>( S_2 ) (ml min (^{-1} ) W (^{-1} ))</th>
<th>MRT(_A) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. 60 r.p.m.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group mean ± s.d.</td>
<td>1.88 ± 0.47</td>
<td>25.4 ± 6.1</td>
<td>131 ± 41</td>
<td>312 ± 41</td>
<td>3.59 ± 0.60</td>
<td>48.4 ± 7.0</td>
<td>9.1 ± 0.9</td>
<td>11.0 ± 1.3</td>
</tr>
<tr>
<td>SPR mean ± s.d.</td>
<td>1.78 ± 0.39</td>
<td>22.1 ± 3.9</td>
<td>119 ± 34</td>
<td>299 ± 41</td>
<td>3.57 ± 0.53</td>
<td>44.5 ± 4.0</td>
<td>8.6 ± 0.9</td>
<td>10.9 ± 1.3</td>
</tr>
<tr>
<td>END mean ± s.d.</td>
<td>1.99 ± 0.55</td>
<td>28.8 ± 6.4(^a)</td>
<td>143 ± 46</td>
<td>325 ± 40</td>
<td>3.62 ± 0.71</td>
<td>52.3 ± 7.3(^a)</td>
<td>9.7 ± 0.7</td>
<td>11.1 ± 1.3</td>
</tr>
<tr>
<td><strong>B. 100 r.p.m.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group mean ± s.d.</td>
<td>1.85 ± 0.40</td>
<td>25.1 ± 5.6</td>
<td>80 ± 41(^b)</td>
<td>306 ± 48</td>
<td>3.55 ± 0.64</td>
<td>47.8 ± 7.7</td>
<td>6.5 ± 3.2(^a)</td>
<td>9.0 ± 1.4(^a)</td>
</tr>
<tr>
<td>SPR mean ± s.d.</td>
<td>1.72 ± 0.27</td>
<td>21.5 ± 2.7</td>
<td>67 ± 19</td>
<td>295 ± 48</td>
<td>3.47 ± 0.55</td>
<td>43.2 ± 4.3</td>
<td>5.1 ± 4.1</td>
<td>9.1 ± 1.8</td>
</tr>
<tr>
<td>END mean ± s.d.</td>
<td>1.99 ± 0.48</td>
<td>28.8 ± 5.5(^a)</td>
<td>93 ± 54</td>
<td>317 ± 50</td>
<td>3.63 ± 0.76</td>
<td>52.4 ± 7.3(^a)</td>
<td>7.9 ± 1.2</td>
<td>9.0 ± 1.0</td>
</tr>
</tbody>
</table>

\( \bullet \) GET, gas exchange threshold; \( W_{\text{GET}} \), work rate at GET; \( S_1 \), slope of \( V_O_2/W \) up to GET, excluding lag in \( V_O_2 \) at the start of the ramp; \( S_2 \), slope of \( V_O_2/W \) from GET up to \( V_O_2\text{Peak} \) or beginning of non-linear change in slope; MRT\(_A\), mean response time (see data analysis for details); SPR, sprint-trained athletes; END, endurance-trained (cross-country) athletes. Significant main effect for r.p.m. is designated at the 100 r.p.m. GROUP mean, while main effect for group (END versus SPR) is in the END group.

**Figure 1.** Incremental ramp power output (in W, continuous line) and \( V_O_2 \) (in l min \(^{-1} \)) versus time (s)

Data for one representative subject at 60 (●) and 100 r.p.m. (○).
test according to the manufacturer’s instructions. The $O_2$ and $CO_2$ analysers were calibrated using gases of known concentrations that spanned the expected range of expired gases. The volume signal was calibrated with a syringe of known volume (3.0 l). Heart rate was monitored by an electrocardiogram with electrodes placed in a modified lead I arrangement.

For all exercise tests, the $\dot{V}_{O_2}$ breath-by-breath data were converted to 10 s intervals and time aligned to the start of the exercise bout. For each of the two incremental ramp tests, $\dot{V}_{O_2,\text{Peak}}$ and $W_{\text{Peak}}$ were defined as the highest 10 s value seen during exercise. Estimation of the GET was performed by the visual inspection of the changes in $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ ($V$-slope; Beaver et al. 1986), ventilatory equivalents of $O_2$ ($\dot{V}_{E}/\dot{V}_{O_2}$) and $CO_2$ ($\dot{V}_{E}/\dot{V}_{CO_2}$), and end-tidal tensions of $O_2$ ($P_{ET, O_2}$) and $CO_2$ ($P_{ET, CO_2}$; Wasserman, 1984). The slope of the increase in $\dot{V}_{O_2}$ as a function of work rate ($\Delta \dot{V}_{O_2}/\Delta W$) was also calculated for regions below ($S_1$) and above ($S_2$) the estimated GET, after the exclusion of any non-linear responses at the beginning of the ramp (representing the mean response time, MRT$_A$) and as $\dot{V}_{O_2,\text{Peak}}$ was approached. The MRT$_A$ was determined by the temporal difference between the beginning of the ramp increase in power output and the intersection of the $S_1$ regression line with the 30 W baseline value (Wasserman, 1981).

Critical power (CP) and anaerobic work capacity (AWC) were determined by fitting the work rate versus

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{Two-parameter group mean estimation ($n = 11$) of CP and AWC at 60 and 100 r.p.m.}
\end{figure}

\begin{itemize}
\item A, non-linear (hyperbolic) work rate versus time to fatigue.
\item B, work rate versus (time to fatigue)$^{-1}$ (linear).
\end{itemize}

Each data point represents the group mean time to fatigue for that specific imposed exhaustive workload. The curve fit was generated using the group means for the CP and AWC parameters.
time-to-fatigue data to both hyperbolic (power versus time to fatigue) and linear equations (power versus (time to fatigue))\(^{-1}\); Poole et al. 1988). The hyperbolic relationship was fitted by the following equation:

\[ t = \frac{a}{(P - b)}, \]

where \( t \) is time to fatigue (in s), \( P \) is the power output (in W), \( b \) represents CP (in W), and \( a \) represents the AWC (in J). In addition, \( a \) and \( b \) were defined by the linear transformation:

\[ P = at^{-1} + b. \]

Note that for both transformations, CP is reported in its traditional units of watts. For each pedalling frequency (60 and 100 r.p.m.), each subject performed one 8 min test at the CP from the non-linear model. The \( \dot{V}_O_2 \) at CP was determined from the initial, predominant \( \dot{V}_O_2 \) rate. Therefore, we determined the CP-\( \dot{V}_O_2 \) min following the onset of a heavy exercise intensity work transformation:

\[ A = \frac{\dot{V}_O_2}{\dot{V}_O_2 \text{peak}} \]

where \( t \) was fitted by the following equation:

\[ A = \frac{\dot{V}_O_2}{\dot{V}_O_2 \text{peak}} = \frac{a}{(P - b)}, \]

Note that for both transformations, \( \dot{V}_O_2 \) is reported in its traditional units of \( \text{l min}^{-1} \). For each pedalling frequency (60 and 100 r.p.m), each subject performed one 8 min test at the CP from the non-linear model. The \( \dot{V}_O_2 \) slow component starts at approximately 2 min following the onset of a heavy exercise intensity work rate. Therefore, we determined the CP-\( \dot{V}_O_2 \) by averaging the \( \dot{V}_O_2 \) response over a 30 s period from 105 to 135 s after the onset of the pedal rate-specific CP. In addition, the end-exercise \( \dot{V}_O_2 \) (\( A_{\text{end}} \)) at CP was determined by averaging the \( \dot{V}_O_2 \) over the last 30 s of the CP-ride at both pedal frequencies.

### Statistical analyses

Significant differences for various responses (CP, CP-\( \dot{V}_O_2 \), AWC etc.) between 60 and 100 r.p.m. and between the END- and SPR-trained athletes were tested by two-way ANOVA with repeated measures across two pedal rates. Tukey’s post hoc test was performed if statistical significance was obtained to identify which groups differed. Relationships between variables were examined using a Pearson Product Moment Linear Correlation Analysis (degrees of freedom = \( N - 2 \)). Statistical significance was declared when \( P < 0.05 \) (for correlation coefficients, \( N = 11, r \geq 0.521; N = 6, r \geq 0.73; \) and \( N = 5, r \geq 0.81 \)). All values are reported as means \( \pm \) s.d.

### Results

#### Subject characteristics

Subjects’ mean age, height and body weight were 20 \( \pm \) 1.98 years, 179 \( \pm \) 6.1 cm, and 74.5 \( \pm \) 10.2 kg, respectively. The mean age, height and body weight for the sprint athletes (SPR) were 20.3 \( \pm \) 2.1 years, 180 \( \pm \) 7.0 cm and 80.1 \( \pm \) 9.6 kg, and for the endurance athletes (END) 20.8 \( \pm \) 2.0 years, 179 \( \pm \) 6.0 cm and 69.0 \( \pm \) 7.9 kg, respectively. The body weight difference

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**Table 2. Critical power and critical power-\( \dot{V}_O_2 \) data**

<table>
<thead>
<tr>
<th>Group</th>
<th>Critical Power (CP) (W)</th>
<th>CP (% ( \dot{V}_O_2 ) peak)</th>
<th>AWC (J)</th>
<th>Endurance (END)</th>
<th>Sprint (SPR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 r.p.m.</td>
<td>207 ( \pm ) 53</td>
<td>66.1 ( \pm ) 10.60</td>
<td>20216 ( \pm ) 9528</td>
<td>178 ( \pm ) 7.90</td>
<td>148 ( \pm ) 5.00</td>
</tr>
<tr>
<td>100 r.p.m.</td>
<td>205 ( \pm ) 52</td>
<td>65.1 ( \pm ) 10.60</td>
<td>20709 ( \pm ) 9528</td>
<td>178 ( \pm ) 7.90</td>
<td>148 ( \pm ) 5.00</td>
</tr>
</tbody>
</table>

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between the SPR and END athletes was not statistically significant ($P = 0.09$).

**Incremental ramp data**

Figure 1 shows the $\dot{V}_O_2$ response for one subject during the incremental tests at 60 and 100 r.p.m. Group mean and submaximal data for incremental ramp tests are presented in Table 1A (60 r.p.m.) and B (100 r.p.m.), respectively, along with the means for both athlete groups. There were no significant differences between either pedalling frequencies or athlete groups for $\dot{V}_O_2$Peak (in l min$^{-1}$), $\dot{W}$Peak (in W), the $\dot{V}_O_2$ at the GET ($\dot{V}_O_2$GET), and MRT$\alpha$. However, the work rate at the GET ($\dot{W}$GET, in W, and as a percentage of $\dot{W}$Peak), $S_1$ and $S_2$ were significantly lower at 100 r.p.m. Also, the BWT-corrected GET-$\dot{V}_O_2$ and $\dot{V}_O_2$Peak were significantly greater for the END athletes at both pedal frequencies.

**Critical power and anaerobic work capacity**

The pooled group mean values for the typical two-parameter non-linear and linear estimation of CP and AWC are shown in Fig. 2A and B, respectively, and in
Table 2 for both 60 and 100 r.p.m. Consistent with previous research (Carnevale & Gaesser, 1991; Hill et al. 1995; McNaughton & Thomas, 1996) the 100 r.p.m. CP was significantly lower (by 9%) compared to the 60 r.p.m. CP. The 100 r.p.m. CP also represented a smaller proportion of the pedal rate-specific $\dot{W}_{\text{Peak}}$ when compared to 60 r.p.m. (Table 2). In addition, at both pedalling frequencies the END athletes displayed a significantly greater CP (Table 2 and Fig. 3), which also represented a greater percentage of the pedal rate-specific $\dot{W}_{\text{Peak}}$ (Table 2). There was no significant difference in AWC either in absolute units (J) or scaled to body mass (J kg$^{-1}$; data not shown) between pedal frequencies or athlete groups.

**Critical power-$\dot{V}_{\text{O}_2}$ data**

The absolute $\dot{V}_{\text{O}_2}$ at CP (CP-$\dot{V}_{\text{O}_2}$, in l min$^{-1}$) was not significantly different between pedal frequencies or athlete groups (Table 2). In addition, there was no significant difference in the body weight-adjusted CP-$\dot{V}_{\text{O}_2}$ (in ml min$^{-1}$ kg$^{-1}$) between pedal frequencies; however, between groups the END athletes displayed a significantly greater relative CP-$\dot{V}_{\text{O}_2}$ (in ml min$^{-1}$ kg$^{-1}$) at both pedal frequencies. There was no significant difference in the CP-$\dot{V}_{\text{O}_2}$ as a percentage of $\dot{V}_{\text{O}_2}\text{Peak}$ between pedal frequencies; however, again, between groups both the CP-$\dot{V}_{\text{O}_2}$ and $A_{\text{tot}}$ as percentages of $\dot{V}_{\text{O}_2}\text{Peak}$ were significantly greater in the

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**Figure 4.** Estimated CP (in W; A), CP-$\dot{V}_{\text{O}_2}$ (in ml min$^{-1}$ kg$^{-1}$; B), and CP-$\dot{V}_{\text{O}_2}$ (as a % of $\dot{V}_{\text{O}_2}\text{Peak}$; C) as functions of $\dot{V}_{\text{O}_2}\text{Peak}$ (in ml min$^{-1}$ kg$^{-1}$) for 60 and 100 r.p.m. * Linear correlations are significant at $P < 0.05$ when $r \geq 0.521$. 

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END athletes compared to the SPR athletes. This resulted from a significant difference between groups at 60 r.p.m., but the difference at 100 r.p.m. did not reach significance ($P = 0.11$ for CP-$V_\text{O}_2$, and $P = 0.14$ for $A_\text{tot}$). There was no significant difference in the $A_\text{tot}$ response (in $\text{l min}^{-1}$) between pedal frequencies and athlete groups (Table 2).

**Correlations**

Both CP (in W) and the $V_\text{O}_2$ response at CP (CP-$V_\text{O}_2$, in $\text{ml min}^{-1} \text{kg}^{-1}$) were significantly correlated with $V_{\text{O}_2\text{Peak}}$ (in $\text{ml min}^{-1} \text{kg}^{-1}$) at both 60 and 100 r.p.m. as illustrated in Fig. 4A and B. However, when the CP-$V_\text{O}_2$ was expressed as a percentage of $V_{\text{O}_2\text{Peak}}$, there was no significant relationship with $V_{\text{O}_2\text{Peak}}$ at either pedal frequency (Fig. 4C). The CP-$V_\text{O}_2$ (in $\text{l min}^{-1}$) was significantly correlated with CP (in W) at both 60 and 100 r.p.m. (Fig. 5). Anaerobic work capacity at 60 and 100 r.p.m. was significantly correlated for both END- and SPR-trained athletes; furthermore, both regression lines were not significantly different from the line of identity (Fig. 6). Finally, the AWC normalized to body weight (in J kg$^{-1}$) was not significantly correlated with either $V_{\text{O}_2\text{Peak}}$ (in $\text{ml min}^{-1} \text{kg}^{-1}$), CP or CP-$V_\text{O}_2$ (in $\text{ml min}^{-1} \text{kg}^{-1}$; $r$ values ranged from 0.01 to 0.45, $P > 0.05$).

**Discussion**

In agreement with previous research, the work rate at critical power (CP) in the present study was significantly lower at 100 compared to 60 r.p.m. (Carnevale & Gaesser, 1991; Hill et al., 1995; McNaughton & Thomas, 1996). However, consistent with our first hypothesis, the $V_\text{O}_2$ response at the CP for 100 r.p.m., expressed either as CP-$V_\text{O}_2$ or as $A_\text{tot}$, was not significantly different from the corresponding $V_\text{O}_2$ response at 60 r.p.m. Furthermore, consistent with our second hypothesis, the CP and the corresponding weight-adjusted CP-$V_\text{O}_2$ (in $\text{ml kg}^{-1} \text{min}^{-1}$) were significantly greater in the END athletes compared to the SPR athletes at both 100 and 60 r.p.m. However, in contrast to our second hypothesis, the AWC was not significantly different between pedalling frequencies or between the END and SPR athletes.

We did not find a significant difference in the CP-$V_\text{O}_2$ response between 60 and 100 r.p.m., even though the 100 r.p.m. CP was significantly lower than the 60 r.p.m. CP. Previous studies have demonstrated that the CP is lower at faster pedalling frequencies (i.e. 90–110 r.p.m.) when compared to slower pedalling frequencies (i.e. 50–70 r.p.m.; Carnevale & Gaesser, 1991; Hill et al., 1995; McNaughton & Thomas, 1996). To our knowledge, however, no previous study has explored the influence of pedal frequency on the $V_\text{O}_2$ response at CP. In fact, only a few studies have reported the $V_\text{O}_2$ response for CP, either in absolute units (l min$^{-1}$) or as a percentage of $V_{\text{O}_2\text{Peak}}$ (Poole et al., 1988; Hill & Smith, 1999; Hill et al., 2002). In these studies, $V_\text{O}_2$ was either measured during 24–25 min (Poole et al., 1988; Hill et al., 2002) or estimated from the sublactate threshold (<LT) $V_\text{O}_2$–work rate slope (Hill & Smith, 1999); in each case, $V_\text{O}_2$ represented ~80–90% $V_{\text{O}_2\text{Peak}}$. However, since there is a

![Figure 5. CP-$V_\text{O}_2$ for 60 and 100 r.p.m. expressed in absolute terms (in l min$^{-1}$) as functions of CP (in W) * Linear correlation significant at $P < 0.05$. Symbol descriptions are defined in Fig. 4.](image1)

![Figure 6. Sixty versus 100 r.p.m. AWC in SPR- and END-trained athletes * Linear correlations are significant at $P < 0.05$ ($n = 5$, $r \geq 0.81$; $n = 6$, $r \geq 0.73$).](image2)
‘slow component’ associated with exercise performed in this domain of exercise intensity (Whipp & Ward, 1990; Pringle & Jones, 2002), the \( V_O_2 \) response during cycling at the CP would be time dependent. To avoid this problem, in the present study, we defined the \( V_O_2 \) response at CP (CP-\( V_O_2 \)) as the absolute initial \( V_O_2 \) response at 2 min, with little or no anticipated influence of a slow component (Barstow & Mole, 1991). The initial \( V_O_2 \) response has previously been shown to increase linearly with work rate from light to heavy intensity (Barstow & Mole, 1991). Thus, our description of the \( V_O_2 \) response at the CP should be \( W \) dependent (e.g. Fig. 5) and characteristic of the initial metabolic cost, without any subsequent influence of the slow component.

The decline in CP at 100 versus 60 r.p.m., concomitant with an unchanged CP-\( V_O_2 \), most probably reflects the increased internal power (IP) associated with faster contraction frequencies (Widrick et al. 1992; Francescato et al. 1995; Barstow et al. 1996; Ferguson et al. 2000; Zoladz et al. 2000; Sjogaard et al. 2002). The effect of increased IP on \( V_O_2 \) is typically most easily seen at low work rates (Barstow et al. 1996; Widrick et al. 1992; Zoladz et al. 2000; e.g. Fig. 1). It is less clear whether and how IP changes as work rate increases. On the one hand, both Widrick et al. (1992; cycling) and Sjogaard et al. (2002; knee extension exercise) calculated that IP remained constant at a given contraction rate as external power increased. On the other hand, Ferguson et al. (2000; knee extension exercise) estimated that IP remained constant as power output increased at 60 r.p.m., but progressively fell with increasing power at 100 r.p.m. These discrepancies continued when the metabolic response (measured as \( V_O_2 \)) was plotted as a function of total power. Ferguson et al. (2000) concluded that the oxygen cost was greater, and rose more steeply with increase in total power, at 100 compared to 60 r.p.m., while Sjogaard et al. (2002) found the \( V_O_2 \)-total power relationship to be the same for frequencies ranging from 45 to 105 r.p.m. Resolution of this conflict is beyond the scope of the present study.

Both the CP-\( V_O_2 \) and \( A_{tot} \) expressed as percentage \( V_O_2\text{Peak} \) were not significantly different between pedalling frequencies, but were significantly greater in the END athletes compared to SPR athletes (Table 2). Functionally, these data suggest that END athletes are able to utilize a greater percentage of their aerobic capacity (\( V_O_2\text{Peak} \)) before reaching the metabolic rate representing CP-\( V_O_2 \) than SPR trained athletes are able, and this distinction is more apparent at slower pedal frequencies.

The higher CP (Fig. 3) and corresponding CP-\( V_O_2 \) (in ml kg\(^{-1}\) min\(^{-1}\), Table 2) found in our END athletes is probably attributable to the adaptive training response to long-term endurance training, which enhances oxidative capacity (Gollnick et al. 1972; Costill et al. 1976a,b, 1979; Jacobs et al. 1987). Previous research found a significant correlation between sustainable power output and mitochondrial volume density, and between mitochondrial volume density and \( V_O_2\text{Peak} \) (in ml min\(^{-1}\) kg\(^{-1}\); Hoppeler et al. 1985). In agreement with Hoppeler et al. (1985), we found a significant correlation between the highest sustainable power output (i.e. CP) and \( V_O_2\text{Peak} \) at both 60 and 100 r.p.m. (Fig. 4A).

In agreement with previous research, we did not find a significant difference in the AWC between 60 and 100 r.p.m. (Carnevale & Gaesser, 1991; Hill et al. 1995; McNaughton & Thomas, 1996). This implies that, even if initial motor unit recruitment patterns are different at 100 compared to 60 r.p.m. (Ahlquist et al. 1992; Takaishi et al. 1994; MacIntosh et al. 2000), at fatigue the same

![Figure 7. Incremental ramp \( V_O_2 \) (in l min\(^{-1}\)) with corresponding GET (in l min\(^{-1}\)) and \( V_O_2 \) (in l min\(^{-1}\)) values for the same subject as in Fig. 1 at 60 (●) and 100 r.p.m. (○). Power output is not shown, for clarity. Note the similar \( V_O_2 \) values for the GET and for CP-\( V_O_2 \) at 60 and 100 r.p.m. despite occurring at different times (and thus different power outputs).](image-url)
total amount of ‘anaerobic work’ has been performed. This suggests that fatigue at different pedal frequencies (and contraction velocities) above CP is ultimately associated with recruitment of a similar pool of available motor units, and may be independent of the temporal patterns of recruitment. Furthermore, there was no significant difference in the AWC between END and SPR athletes. However, there was a trend for the AWC to be higher in the SPR athletes compared to the END athletes ($P = 0.11$) which, given the relatively small number of subjects in each group, might reflect a type II error. This trend is consistent with the observations that muscle glycogen and phosphagen pools (ATP and PCr), which are the major anaerobic energy sources and significant determinants of the AWC during high-intensity exercise (Miura et al. 1999, 2000, 2002), may be higher in fast-twitch muscles (Goldspink, 1978). Finally, the association between athlete groups and muscle fibre type populations, recruitment patterns and muscle oxidative capacity in the present study is merely speculative, since fibre composition and enzyme activity were not measured.

On average, when pedalling at 100 r.p.m., the $W_{\text{GET}}$ decreased by approximately 50 W and CP by approximately 18 W compared to 60 r.p.m. This suggests an interesting observation, i.e. that the rate of external $W$ values identifying the moderate intensity exercise domain narrow, while the range of external $W$ values associated with heavy exercise ($W_{\text{GET}}$ to CP) widen, at 100 compared to 60 r.p.m. However, the GET-$V_{O2}$, CP-$V_{O2}$, and their respective percentages of $V_{O2\text{Peak}}$ were not significantly different between pedalling frequencies. Davis et al. (1982) found a similar constancy of the GET-$V_{O2}$ and $V_{O2\text{Peak}}$ for slopes of the ramp increase in work rate during incremental exercise ranging from 20 to 50 W min$^{-1}$. Our results, like those of Davis et al. (1982), suggest that, despite differences in external $W$, the $V_{O2}$ identifying the relevant intensity domains (GET-$V_{O2}$ and CP-$V_{O2}$) present unique aerobic parameters for a given individual and thus are independent of the work rate profiles (ramp or pedal rate) used to discern them. In the present study, this may be attributed to the elevated baseline $V_{O2}$ (BSL-$V_{O2}$), and lower $\Delta V_{O2}/\Delta W$ relationship (both $S_1$ and $S_2$, Table 1) at 100 compared to 60 r.p.m., with no significant difference in the $V_{O2\text{Peak}}$ between pedalling frequencies.

Pedalling frequency directly affects muscle contraction velocity and the selective recruitment of muscle units necessary for the performance of an exercise task. For the same power output, pedalling at low frequencies (e.g. 50 r.p.m.) requires substantial force production, whereas faster pedalling frequencies (e.g. 100 r.p.m.) require a faster contraction velocity, both of which have been shown to recruit fast-twitch fibres (Ahlquist et al. 1992). Furthermore, as contraction velocity increases, the contribution of faster fibres is envisioned to become a greater percentage of the total power output, not only because the optimal velocity for maximum power generation of the slower fibres may be exceeded but also because fibres with a higher maximal shortening velocity will produce more power than slower fibres at their respective optimal velocity (Beelen & Sargeant, 1991). Thus, it is possible that our faster pedalling frequency (100 r.p.m.) may have been slightly higher than the optimal contraction velocity for the slow-twitch fibres and at the same time slightly closer to the optimal velocities of the fast-twitch fibres (Ahlquist et al. 1992; Barclay, 1994, 1996; Sargeant, 1994). This would suggest that SPR athletes should theoretically be more ‘efficient’ at a faster pedalling frequency, owing to a greater percentage of fast fibres compared to END athletes. However, our data showed (albeit with a small number of subjects) that the faster pedalling frequency (100 r.p.m.) compromised CP similarly in both END (8.7%) and SPR athletes (8.5%), with no change in the CP-$V_{O2}$.

In summary, CP was significantly lower at 100 compared to 60 r.p.m. and significantly higher in END athletes at both pedalling frequencies compared to SPR athletes. However, CP-$V_{O2}$ was similar between 100 and 60 r.p.m. for each group. The relative CP-$V_{O2}$, scaled to body mass was significantly greater at both 100 and 60 r.p.m. in the END athletes compared to the SPR athletes. In conclusion, our findings suggest that the CP-$V_{O2}$ is a metabolic rate, which is similar in a given subject despite being achievable at different external $W$ and pedal frequency combinations (Fig. 7). Thus, CP-$V_{O2}$ may be considered a parameter of aerobic function. While not measured in the present study, we speculate that this metabolic rate is determined at least in part by the total power output (external + internal).

References


