Critical power as an endurance index

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The relationship between exhaustion time ($t_{lim}$) and the work performed at the end of constant-power exercises can be described by a linear relationship ($W_{lim} = a + b t_{lim}$) for work involving the whole body (eg cycling) or part of the body (eg knee extensions). The slope $b$ in the equation is termed the critical power and has been proposed as an index of the capacity to perform work over a long period of time. The first objective of the present study was to compare the values of slopes $b$ calculated from whole-body work of short duration, ie maximal and supra-maximal cycling exercises (slope $b_1$), with the values calculated from the same work, the durations of which were between 3.5 and 35 min (slope $b_3$), as in the protocols used by Scherrer and Monod (1960) for body-part work. Slope $b_1$ was significantly higher than slope $b_3$ in 10 subjects who performed 5 cycling exhausting exercises (60, 73, 86, 100 and 120% of maximal aerobic power (MAP) in watts). Exhaustion times corresponding to power outputs equivalent to $b_1$ and $b_3$ were equal to 29.0 ± 19.1 min and 48.6 ± 9.8 min respectively. Moreover, the exhaustion times at 60 and 73% MAP were significantly correlated with slope $b_3$ (expressed in %MAP) but not with slope $b_1$. Consequently, slope $b_3$ should be considered as the critical power instead of slope $b_1$ as in some studies in the literature (Moritani et al, 1981). The second objective was to study the physiological significance of the critical power (slope $b_3$) of whole-body work (cycling). The workload that corresponded to a lactate steady state was not significantly different from $b_3$ (68.8 ± 6.0 vs 68.7 ± 6.3% MAP). Nevertheless, slope $b_1$ represents a workload corresponding to a slight but significant drift of heart rate or oxygen uptake. These results probably explain why $b_1$ is a power which can be maintained for a long time but not beyond about 1 h in an average subject.

Keywords: fatigue, endurance, human performance, aerobic fitness, ergometry, workload

Scherrer and Monod (Scherrer et al, 1954; Scherrer and Monod, 1960; Monod and Scherrer, 1965) proposed a linear relationship between exhaustion time ($t_{lim}$) of body-part work performed at constant load (power output $P$) and the total amount of work performed at exhaustion, $W_{lim}$:

$$W_{lim} = a + b t_{lim}$$

(1)

As $W_{lim} = P t_{lim}$, Equation (1) is equivalent to

$$P = \frac{a}{t_{lim}} + b$$

(2)

or

$$t_{lim} = \frac{a}{P - b}$$

(3)

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These relationships were found for work whose $t_{lim}$ ranged from 3 to 35 min and which consisted in flexions or extensions of the elbow or the knee in the study by Scherrer and Monod. According to these authors, the slope of the linear relationship has the meaning of a workload that can be sustained for a long time (several hours), and parameter $a$ is equivalent to an energy store (oxygen bound to myoglobin and anaerobic capacity). Slope $b$ was called critical power. In theory, it represents the maximal power that a subject could sustain for several hours. For an exercise of higher power than $b$, the energy store $a$ is used up during the work, and $t_{lim}$ can be calculated from the previous relationship: $t_{lim} = a/(P - b)$.

A similar linear relationship was found between distances and world records or individual best performances in running for events whose durations ranged from 2.5 to 30 min (Ettema, 1966; Lechevalier et al, 1989; Sid-Ali et al, 1991). As running cost (approximately 1 kcal km$^{-1}$ kgBW$^{-1}$ or 4.185 kJ km$^{-1}$ kgBW$^{-1}$) is independent of velocity between 10 and 20 km h$^{-1}$ (Margaria et al, 1963), each distance corresponds to the same amount of energy (kJ) even if the velocities are different. Therefore, the slopes of these relationships...
correspond to a critical velocity whose meaning is similar to that of a critical power.

Likewise, for an ergonomist, the concept of critical power could be useful for the determination of the workload that can be sustained for a long time. For load-carrying work, the relationship between load $F$ and exhaustion time $t_{lim}$ proposed by Evans et al (1983) was

$$t_{lim} = \frac{k}{(F)^n} \quad (4)$$

or

$$\log(t_{lim}) = \log(k) - n \log(F) \quad (5)$$

Such a relationship does not give information on the load that can be carried for a long time. Moreover, the accuracy and the reliability of the computed values of $k$ and $n$ are questionable. The experimental data can also be expressed according to the concept of critical power. Although the directions of the movement (walking) and gravity forces are perpendicular, and consequently there is no physical work, we can consider the product of load $F$ and distance $d$ as an equivalent of a physiological work ($W_{lim}$).

$$W_{lim} = Fd = a + b \ t_{lim} \quad (6)$$

However, this linear relationship fits the experimental data for exercise durations higher than 2 min only, as shown in Figure 1, which corresponds to the results of subject R.P. in the study by Evans et al (1983). The slope of the $t_{lim}$-$W_{lim}$ relationship is clearly steeper for $t_{lim}$ less than 2 min. Therefore the critical power of these load-carrying tasks should be calculated from exhaustion times higher than 2 min, as in the studies of Scherrer and Monod (1960) on body-part work.

Moritani et al (1981) found the same linear relationship ($t_{lim}$-$W_{lim}$) for cycling exercises on a Monark ergometer. These authors interpreted their results according to the concepts of Scherrer and Monod (1960). However, their protocol consisted in supra-maximal exercises whose durations were less than a few minutes, and the validity of such a critical power is dubious. Indeed, the critical power calculated from these brief supra-maximal cycling exercises corresponds to an average exhaustion time that is rather short, and equal to 33 min (Housh et al, 1989).

From a practical point of view, these results show that the critical power calculated from work of durations between 3 and 30 min is indicative of the ability of the subjects to perform physical work involving a body part for a prolonged period. Moreover, Moritani et al (1981) showed a significant correlation between the critical power calculated from supra-maximal and maximal exercises and $V_{max0}$, for cycling exercises. This latest result is also interesting, as $V_{max0}$ is the main factor limiting the performance in long-distance cycling or running (Astrand and Saltin, 1961).

The first objective of the present study was to study the validity of the critical powers calculated from different ranges of exhaustion times. Consequently, we compared the values of slopes $b$ calculated from work involving the whole body, calculated from: (a) short-duration maximal and supra-maximal cycling exercises (slope $b_1$); (b) cycling exercises of durations lower than 35 min (slope $b_2$); or (c) from cycling exercises of duration between 3.5 and 35 min only (slope $b_3$), as in the protocols used by Scherrer and Monod (1960) for work involving part of the body.

The second objective was to study the physiological significance of the critical powers of whole-body work. We studied: (a) the evolution of heart rate, oxygen uptake and lactate concentration corresponding to the workloads equivalent to the different slopes $b$; (b) the relationships between critical powers and some indices of the maximal performance ability in long-lasting exercises (maximal oxygen uptake and aerobic endurance, i.e. the subject's capacity to maintain a high percentage of maximal aerobic power for a long time).

**Methods**

Ten male healthy subjects, physical education students (body mass $74.1 \pm 7.6$ kg; height $178.3 \pm 4.6$ cm; ages $21.6 \pm 1.1$ years) participated in the study.

The work was cycling exercises, which were performed on the same friction-loaded Monark Ergometer (model 864), which provided a constant power at the subject's cyclic frequency. Pedal rates were monitored by means of a device that consisted of a disc with 60 black sectors and a photoelectric cell.

Cycling rates were controlled by an XT PC, which imposed the pace by emitting sounds at constant intervals. The photoelectric cells of the cycle ergometer were linked to the microcomputer, which registered and displayed the difference between the total work performed by the subject and the total work required at that time.

Oxygen uptake was measured by means of the open-circuit method. Expired gas was collected alternately with two 180 l Tissot's spirometers every minute. Fraction of oxygen and carbon dioxide were measured by means of a Beckman OM11 analyser and an infrared Cosma analyser respectively.

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**Figure 1** Relationship between exhaustion time of a load-carrying task and work performed at exhaustion (unpublished personal data corresponding to subject R.P. in the study by Evans et al in 1983). Open circles and black dots correspond to exhaustion times lower and higher than 2 min, respectively.
Heart rate was measured and stored by means of a Sport Tester 3000 (Polar, Finland).

Lactate concentration was measured according to the usual micro-enzymatic method (Boehringer’s kit) after deproteinization in perchloric acid (0.7 M) of 100 μl blood samples. Body weight was measured just before the exercise, with a weighing machine whose accuracy was equal to 0.03 kg.

Protocols

Maximal oxygen uptake (VmaxO₂) was measured during an incremental cycling test (20 W increments every 2 min) in the first session. VmaxO₂ represented the oxygen uptake of the last step of the incremental test. Maximal aerobic power (MAP) was considered as the maximal mechanical power output that could be produced from aerobic metabolism alone during the incremental test. MAP was calculated from the experimental individual relationship between heart rate and power output. It was calculated by extrapolation of the linear part of the heart rate–power output relationship up to the individual maximal heart rate (i.e., the highest value measured during the incremental test). In the present study, MAP was slightly lower (around 10 W) than the power output corresponding to the last step of the incremental test.

The subjects performed five exhausting exercises on a Monark cycle ergometer at different loads, which correspond to percentages of MAP measured during the first session (60, 73, 86, 100, and 120 %MAP). Cycling rates were equal to 80 rev min⁻¹. The subjects were considered as exhausted when the difference between the total work performed by the subject and the total work required at that time corresponded to a two revolution lag without being able to accelerate to compensate this lag.

Oxygen uptake and heart rate were measured every minute. Blood samples were collected from the finger tip every 5 min during the first 20 min of exercise and thereafter every 10 min for the long-lasting exercises. Blood was also collected at the end and 2 min after the end of exercise.

The interval between exercise sessions was not less than one week.

Calculations

The work performed at exhaustion, Wlim, was equal to the product of exhaustion time tlim and power output. The slopes of the individual tlim-Wlim relationships were calculated in three different ways. The slope b₁ of the tlim-Wlim relationship was calculated from the maximal and the supra-maximal exhausting exercises (100 and 120 %MAP) only, i.e., loads similar to the previous studies on critical power in cycling exercises in the literature. Two other relationships were calculated according to the least-squares method. The second individual relationships (slopes b₂) were calculated by including all values of tlim lower than 35 min. The third relationships (slopes b₃) corresponded to exercises whose exhaustion times were between 3.5 and 35 min. Exhaustion time corresponding to the workloads equal to b₁ (tlim₁) and b₃ (tlim₃) were calculated by linear interpolation of the experimental individual data concerning power output and tlim.

We assumed that the drift of heart rate and oxygen uptake is linear after an exponential rise at the beginning of the exercise according to Morton’s model (1985), rather than more complicated models (Camus et al., 1988). The heart rate drift and the oxygen uptake drift were estimated as equal to the slope of the linear part of the heart rate–time curve and oxygen uptake–time curve according to the least-squares method. The drifts of heart rate or the drifts of VO₂ corresponding to b₁ and b₂ were estimated by linear interpolation of the individual experimental relationships between workload and heart rate drift or VO₂ drift.

The lactate–time curves between the fifth minute and the end of exercise were fitted with a linear equation according to the least-squares method. At 60% of maximal aerobic power, after an initial increase during the first 5 min, the lactate concentration sometimes decreased before plateauing at a low value at the end of exercise. In such a case, the lactate–time slope was calculated from the descending phase only.

The work load corresponding to the lactate steady state (PSSₘₐₓ), i.e., the workload corresponding to a zero slope of the lactate–time relationship, was expressed as a percentage of MAP and calculated by linear interpolation between two points of the relationship between lactate slopes and workload.

Results

The value of slope b₁ (79.8 ± 5.6 %MAP) was significantly higher (p < 0.01) than slope b₂ (69.7 ± 5.7 %MAP) and slope b₃ (68.7 ± 6.3 %MAP).

The exhaustion time tlim₁ (29 ± 19.1 min) was significantly shorter (p < 0.01) than tlim₃ (48.6 ± 9.8 min).

Oxygen uptake (expressed in %VmaxO₂) measured at the end of exercises at 60 %MAP (69.2 ± 6.2), 73 %MAP (81.2 ± 8.3) and 86 %MAP (95.3 ± 6.7) were, respectively, significantly higher (p < 0.01) than oxygen uptake measured at the fifth minute of exercises at 60 %MAP (63.8 ± 5.6), 73 %MAP (76.1 ± 7.0) and 86 %MAP (87.7 ± 5.6). These values at the fifth minute were close to the expected values that would have taken into account the oxygen uptake at rest (around 3.5 ml min⁻¹ kg⁻¹).

The heart rate drift and VO₂ drift corresponding to b₁ were equal to 0.59 ± 0.27 bpm min⁻¹ and 5.3 ± 4.38 ml min⁻¹ respectively. Therefore b₁ did not correspond to a perfect steady state if heart rate and VO₂ were considered. The drifts for a load corresponding to b₁ were much higher (1.94 ± 1.9 bpm min⁻¹ and 73.0 ± 26.7 ml min⁻¹) respectively, p < 0.01).

The power corresponding to the lactate steady state PSSₘₐₓ and b₁ expressed as a percentage of MAP (b₃ₘₐₓ) were not significantly different (68.8 ± 6.0 vs 67.8 ± 6.3). However, PSSₘₐₓ and b₃ₘₐₓ were not significantly correlated (r = 0.33).

b₁ (W kg⁻¹) was significantly correlated with maximal aerobic power (MAP in W kg⁻¹) and with maximal oxygen uptake (VmaxO₂ in ml min⁻¹ kg⁻¹):
$b_1 = -1 + 1.06 \text{MAP} \quad (r = 0.95, p < 0.01)$

$\text{b}_1 = -1.86 + 0.095 \text{VmaxO}_2 \quad (r = 0.71, p < 0.05)$

$b_1 (\text{W kg}^{-1})$ was not significantly correlated with the exhaustion times of the cycling exercises, expressed in minutes, at 60 %MAP ($t_{\text{lim73\%}}$) ($r = 0.22$) or at 73 %MAP ($t_{\text{lim73\%}}$) ($r = -0.43$). Furthermore, $b_1$ (%MAP) was not significantly correlated with the exhaustion times of the cycling exercises, expressed in minutes, at 60 %MAP ($t_{\text{lim60\%}}$) ($r = 0.51$) or at 73 %MAP ($t_{\text{lim73\%}}$) ($r = 0.03$).

$b_1 (\text{W kg}^{-1})$ was significantly correlated with maximal aerobic power (MAP in \text{W kg}^{-1}) but not with maximal oxygen uptake (\text{VmaxO}_2 in ml min^{-1} kg^{-1}) ($r = 0.23$):

$b_3 = 0.683 + 0.508 \text{MAP} \quad (r = 0.65, p < 0.05)$

$b_3 (\text{W kg}^{-1})$ was significantly correlated with $t_{\text{lim60\%}}$ (min) but not with $t_{\text{lim73\%}}$ (min) ($r = 0.29$). Nevertheless, $b_3$ expressed in %MAP ($b_3\%$) was significantly correlated with $t_{\text{lim60\%}}$ (min) and with $t_{\text{lim73\%}}$ (min) (Figure 2):

$b_3 = 1.473 + 0.0147 t_{\text{lim60\%}} \quad (r = 0.67, p < 0.05)$

$b_3\% = 57.18 + 0.147 t_{\text{lim60\%}} \quad (r = 0.72, p < 0.02)$

$b_3\% = 56.37 + 0.345 t_{\text{lim73\%}} \quad (r = 0.88, p < 0.01)$

**Discussion**

The average value of $b_1$ was identical to those of the critical power measured in the previous studies from supra-maximal cycling exercises (Moritani et al, 1981; Vandewalle et al, 1989). The higher value of $b_1$ when compared with $b_2$ suggests that the relationship between $t_{\text{lim}}$ and $W_{\text{lim}}$ is not truly linear for a large range of $t_{\text{lim}}$.

The same values of $b_3\%$, and the power $P_{\text{SS\%}}$, corresponding to a lactate steady state confirm that $b_3$ is a power that can be maintained for a long time. The lack of correlation between $b_3\%$ and $P_{\text{SS\%}}$ can be explained by the low standard deviation of $b_3\%$ and $P_{\text{SS\%}}$ and probably by the errors in the estimation of $b_3\%$ and $P_{\text{SS\%}}$ due to day-to-day differences in physical fitness. The heart rate drifts and $V_O$, drifts calculated for a workload equal to $b_2$ were low, but not negligible, and probably explained why this workload cannot be maintained beyond 50 min in an average subject.

Our calculated data confirm the experimental data of the study by Housh et al (1989), which showed that the average exhaustion time (35 min in their study versus 29 min in the present study) of a work performed at a power equal to slope $b_1$ is rather short. The drifts of $V_O$ and heart rate corresponding to a workload equal to $b_1$ are much higher and the exhaustion time is significantly shorter than the same data calculated for $b_3$.

Slope $b_1$ is correlated with MAP or $\text{VmaxO}_2$ in agreement with the results of Moritani et al (1981). Slope $b_1$ is not correlated with $t_{\text{lim73\%}}$ and $t_{\text{lim60\%}}$, which express the subject’s capacity to maintain a high percentage of MAP for a long time, ie aerobic endurance. In contrast, $b_3\%$ is correlated with $t_{\text{lim60\%}}$ and $t_{\text{lim73\%}}$ but not with $\text{VmaxO}_2$. These results suggest that $b_1$ is an indicator of aerobic power rather than an index of aerobic endurance, and vice versa for $b_3$.

As critical power represents a workload that can be sustained for a long time, the present study suggests that the critical power of work involving the whole body should be calculated from exercises with durations longer than 3 min (slope $b_3$ instead of slope $b_1$ as in some studies in the literature), ie according to a protocol similar to that used by Scherrer et al (1954, 1960, 1965) for work involving part of the body or by Ettema (1966), Lechevalier et al (1989) and Sid-Ali et al (1991) for running exercises. Therefore, critical power could be included in the set of indicators of physical fitness (Rcilly, 1991), provided that slope $b$ is computed from exercises that last between 3 and 35 min. For an ergonomist, slope $b_3$ could help with the determination of the maximal workload of a continuous task whose duration is shorter than 50 min. Nevertheless, for long-duration tasks (eg 8 h), it is likely that another critical power should be calculated from higher values of $t_{\text{lim}}$ (from 1 to 4 h). Thus the concept of critical power could be valuable for those occupations where high power outputs are demanded for a prolonged period, such as occupations in the armed forces.

**Conclusion**

Critical power for whole-body work must be calculated from $t_{\text{lim}}$ between 3 and 35 min as in the study by Scherrer and Monod (1960) for a body-part work. The study of heart rate drift, $V_O$, drift and lactate steady state suggests that critical power is a good indicator of subject’s endurance. Critical power could be useful in the determination of the maximal workload that can be sustained in daily activities. Indeed, although the determination of critical power from sub-maximal exercise intensities is time-consuming, it is possible to predict the maximum exercise intensity that can be sustained for up to about 1 h without expensive laboratory measurements such as oxygen uptake and the blood lactate response to sub-maximal exercise.

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