REVIEW ARTICLE

Sports Medicine 16 (4): 237-254, 1993
0112-1642/93/0010-0237/$09.00/0

SPO1 281

The Critical Power Concept
A Review

David W. Hill
Exercise Physiology Laboratory, University of North Texas, Denton, Texas, USA

Contents

Summary

The basis of the critical power concept is that there is a hyperbolic relationship between power output and the time that the power output can be sustained. The relationship can be described based on the results of a series of 3 to 7 or more timed all-out predicting trials. Theoretically, the power asymptote of the relationship, CP (critical power), can be sustained without fatigue; in fact, exhaustion occurs after about 30 to 60 minutes of exercise at CP. Nevertheless, CP is related to the fatigue threshold, the ventilatory and lactate thresholds, and maximum oxygen uptake ($\dot{V}O_{2max}$), and it provides a measure of aerobic fitness. The second parameter of the relationship, AWC (anaerobic work capacity), is related to work performed in a 30-second Wingate test, work in intermittent high-intensity exercise, and oxygen deficit, and it provides a measure of anaerobic capacity. The accuracy of the parameter estimates may be enhanced by careful selection of the power outputs for the predicting trials and by performing a greater number of trials. These parameters provide fitness measures which are mode-specific, combine energy production and mechanical efficiency in 1 variable, and do not require the use of expensive equipment or invasive procedures. However, the attractiveness of the critical power concept diminishes if too many predicting trials are required for generation of parameter estimates with a reasonable degree of accuracy.

1. The Critical Power Concept

The relationship between power output and time to exhaustion during 3, 4 or 5 bouts of repetitive lifting exercises performed using different isolated muscle groups was reported by Monod and Scherrer (1965). They noted a hyperbolic relationship between power output and time to exhaustion and transformed this into a linear relationship between total work performed and time to exhaustion. Critical power (CP) was defined as the slope of the regression of work on time. CP was identified as the maximum rate that could be sustained 'for a very long time without fatigue' (Monod & Scherrer 1965) and it was suggested that 'when the imposed power is inferior or equal to the critical power, . . . exhaustion cannot occur'.

Moritani and colleagues (1981) extended the critical power concept to cycling exercise and provided evidence of the aerobic nature of the CP parameter, which was highly correlated with the ventilatory anaerobic threshold. They also provided evidence of the anaerobic nature of the *y*-intercept of the work-time relationship [the *y*-intercept will be referred to as anaerobic work capacity (AWC)], which was unaffected by hypoxia. Whipp and colleagues (1982) calculated parameters of the power-time relationship by rearranging into a second linear model and regressing power against the inverse of time.

Three mathematically equivalent models have been used to describe the power-time or work-time relationship and to derive estimates of the parameters of the relationship (CP and AWC). The 3 models are:

(1) a nonlinear power-time model, where time = AWC/(power − CP);

(2) a linear power-1/time model, where power = CP + (AWC • 1/time); and

(3) a linear work-time model, where work = AWC + (CP • time).

Figures 1 to 3 provide graphical representations of the various models for a set of 5 data points. Accompanying each panel is an equation relating the parameters of the model. For each model, the 2 parameters are referred to as CP and AWC. In the literature many different names are used for each of the parameters. One reason for the variety of labels is that there are 3 models available to use in the estimation of the parameters. In the work-time model, CP is the slope of the relationship (and is often called *b*); in the power-1/time model, CP is the intercept (and may be called *a* or the *y*-intercept); and in the nonlinear model, critical

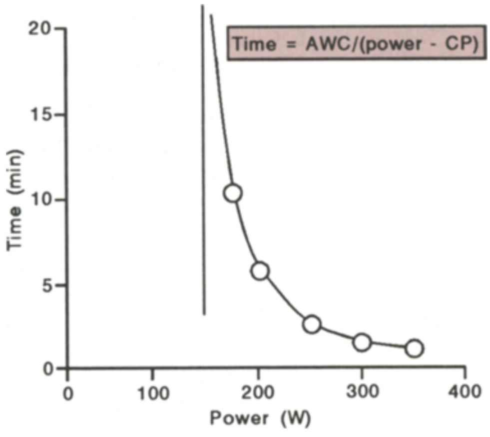

Fig. 1. The nonlinear power-time relationship presented graphically and mathematically.

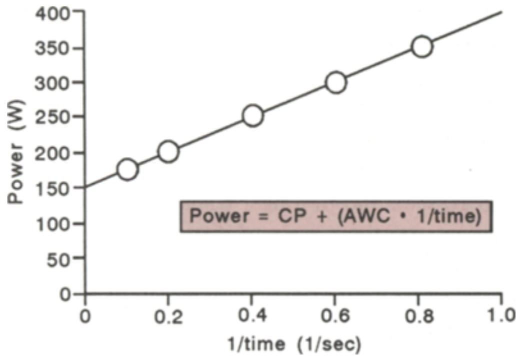

Fig. 2. The linear power-1/time relationship presented graphically and mathematically.

power is the asymptote (and has been identified as θ_{PA}, θ_f, P_{LL}, θ_{LL}, and W_a). AWC is the *y*-intercept of the work-time relationship, the slope of the power-1/time relationship, and the degree of curvature in the hyperbolic relationship. The 2 parameters will be referred to as CP and AWC throughout this article.

2. *Estimating Parameters of the Power-Time Relationship*

The critical power concept is based on a hyperbolic relationship between power output and time to exhaustion. To describe the relationship and to estimate values of the CP and AWC parameters, volunteers perform a series of all-out exercise tests. In theory, only 2 points are necessary for derivations using the linear models. In practice, investigators have used from 2 to over 7 data points to reduce the error associated with the parameter estimates. Recommendations have been made for the optimal duration of the exercise trials predicting CP and AWC. Other factors, such as choice of ergometer or choice of pedalling cadence, may also affect the reliability or validity of parameter estimates.

2.1 Number of Trials

The critical power concept is attractive because it generates estimates of the CP and AWC parameters using only a calibrated ergometer and a stopwatch. A drawback to the procedure is that participants must perform multiple all-out exhaustive exercise tests. Some laboratory protocols only rest participants for 30 minutes between 2 all-out efforts (Housh et al. 1990), while some protocols spread trials over a 12-hour period (Jenkins & Quigley 1991). However, most trials require at least 24 hours of recovery between efforts (Carnevale & Gaesser 1991; Gaesser & Wilson 1988; Jenkins & Quigley 1990; Poole et al. 1990; Smith & Hill 1993).

Because estimation of the CP and AWC parameters requires participants to be rested before a trial and ready to give a 100% effort on several occasions, efforts have been made to identify the minimum number of data points necessary to describe the power-time relationship accurately. Housh et al. (1990) had participants perform 4 all-out tests. Parameter estimates were derived from all possible combinations of 2, 3, or 4 trials. They reported that CP estimates from 2 predicting tests were highly correlated ($r \geqslant 0.96$) with the CP estimates derived from 4 predicting tests when the duration of the 2 tests differed by over 2.7 minutes. When the duration of the 2 trials differed by over 5 minutes, parameter estimates were associated with low standard error of the estimate (SEE) and correlations between the parameter estimates and the estimates derived from all 4 trials were very high ($r \geqslant 0.98$). Therefore, accurate estimates of CP

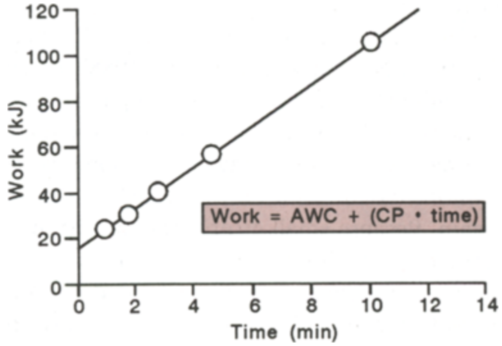

Fig. 3. The linear work-time relationship presented graphically and mathematically.

and AWC could be derived from only 2 predicting trials, using the linear work-time model, if the duration of the trials was between 1 and 10 minutes and the trials were 5 minutes or more apart (Housh et al. 1990). However, the validity of the parameter estimates was not directly assessed, although they were judged to be accurate based on both the low SEE and on the high correlation between them and the estimates derived from the same 2 trials plus 2 others.

2.2 Duration of Exercise Trials

The range of exercise durations is also a consideration in trials. In the original studies with single-muscle lifting activities participants performed 4 or 5 exercise bouts from which the parameters of the work-time relationship were derived (Monod & Scherrer 1965); for some muscle groups, the duration of the predicting trials ranged from 2 to 10 minutes, while in others, the range was from 2 to 30 minutes. Studies of whole-body exercise, beginning with the work of Moritani et al. (1981), have usually limited the longest trial to between 5 and 10 minutes, although raw data are not provided in all reports.

Poole (1986) stated that the exercise in trials should range from 1 to 10 minutes. Many investigators have quoted that assertion, yet even when the longest trials are less than 5 or 6 minutes duration investigators have noted excellent fit of their data to whichever of the 3 models they chose to use (Carnevale & Gaesser 1991; Jenkins & Quigley 1992, 1993; Nebelsick-Gullet et al. 1988). If there is a relationship between power output and time to exhaustion, then the duration of predicting exercise tests should be immaterial as long as they are within the range of times defined by the relationship. Because small errors are inherent in any measured data point, the recommendation of Housh and colleagues (1990) that the duration of long and short trials be about 5 minutes different, and the recommendation of Poole (1986) that durations should range from 1 to 10 minutes seem logical.

2.3 Reliability of Parameter Estimates across Sets of Exercise Trials

Poole and colleagues (1988) evaluated the reliability of performance of different trial intensities. In trials of 4 minutes there was a 2 to 4% variation (5 to 10 sec), and in longer trials (8 min) there was a larger variation of about 4 to 6% (20 to 30 sec) in performance. As each of the 8 participants repeated only 1 trial, the findings could not be extrapolated to the effects that performing repeated trials would have on the magnitude of derived parameters of the power-time relationship. However, assuming that variation was a result of a learning effect, the CP estimates generated by a second set of predicting trials would be expected to be larger and AWC estimates would be unchanged.

Three studies have evaluated the reliability of parameter estimates derived from 2 sets of exercise prediction trials. Gaesser and Wilson (1988) had 11 male participants perform 2 sets of 5 trials, each performed on a separate day with less than a week separating the first and second series. The test-retest correlation coefficient for CP was 0.96. The retest estimate was 3% higher ($p < 0.05$) than the first test estimate. The test-retest correlation coefficient for AWC was 0.79; there was no difference between the mean retest and mean first test AWC estimates although 4 of the 11 retest values differed by more than 15% from the first-test estimates (Gaesser & Wilson 1988).

Nebelsick-Gullett and colleagues (1988) also assessed the reliability of CP and AWC estimates. They had 25 female participants perform 2 sets of 3 trials; 3 trials were performed on 1 day, with approximately 30 minutes or longer recovery between each, and then repeated 1 to 7 days later. They reported a test-retest correlation coefficient of 0.94 for CP. The test-retest correlation for AWC was lower (0.87) but still high. There were no differences between the mean values for the first and second of estimates of either CP or AWC.

Smith and Hill (1993) assessed the stability of parameter estimates in 13 men and 13 women. Parameter estimates were derived using the nonlinear power-time model and the results of 5 predicting trials. Like Gaesser and Wilson (1988) and Nebelsick-Gullett et al. (1988), they reported higher test-retest correlations for CP than for AWC. CP correlation coefficients were 0.92 for the men and 0.90 for the women. AWC correlation coefficients were 0.80 for the men and 0.64 for the women. Mean values for CP from the second set of trials were higher than first-test values: 5% higher in the men and 6% higher in the women, with an effect size of 1.0 to 1.1. Mean AWC estimates were unchanged.

Indirect assessment of the reliability of the CP and AWC parameter estimates can also be made by evaluating the stability of these estimates generated before and after training programmes. For example, programmes designed to influence only CP should not affect the estimate of AWC and programmes designed to influence AWC should not affect CP. Small improvements in aerobic power after anaerobic training or small improvements in anaerobic capacity after endurance training might not be unexpected because anaerobic training has a considerable aerobic component and endurance training, especially high-intensity intermittent training, would have an anaerobic component; reductions in a parameter after training might be harder to explain.

Differences between studies in the reported test-retest correlations may reflect differences in sample size and homogeneity. Differences within studies (between test-retest correlations for CP and AWC) should be independent of between-study differences. Together, these 3 reports suggest that CP estimates are reliable with test-retest correlation coefficients that are equal to or greater than 0.90 and are similar to test-retest correlation coefficients described in traditional testing of maximal aerobic power (Thoden 1990). For the 11 men of the Gaesser and Wilson (1988) study and the 13 women and 13 men of the Smith and Hill (1993) study there was an increase in the CP estimate based on the results of a second set of 5 trials compared with the estimate generated from the first set of 5 trials; this was not the case for the 25 women of the Nebelsick-Gullett et al. (1988) study, where 2 sets of 3 trials were performed. Test-retest correlation coefficients for AWC estimates were lower than for CP estimates; AWC estimates did not seem to be subject to a consistent trial learning effect.

2.4 Selection of Ergometers, Pedal Cadence and Test End-Points

Description of the power-time relationship requires an ergometer that provides a constant work rate. In tests using Monark or similar ergometers, there are 2 potential sources for error. First, resistance tends to change during a test, and the resistance must continually be adjusted; secondly, the actual work rate is directly related to the pedal cadence. Unless resistance remains constant and the participant maintains exactly the required pedal cadence, the reported work rate will not be equal to the actual power output. However, if cadence fluctuations around the required rate are random, total work will not be affected. Especially near the end of the test, pedal cadence may drop below the reported value without reaching the cut-off criterion: during this period, actual power output will drop below the reported rate and time to exhaustion may actually be extended; however, the magnitude of these errors would be small, especially in the longer tests where a few seconds of exercise represent a small fraction of the total. Secondly, individuals will be required to attempt to maintain a fixed cadence that may or may not be optimal for the individual at that given power output. Use of an electronically-braked cycle ergometer ensures accurate power output independent of pedal cadence.

Metabolic efficiency, or oxygen cost at a given power output, varies at different pedal cadences (Coast & Welch 1985; Gaesser & Brooks 1975; Seabury et al. 1977). Thus, it was postulated that pedal cadence during the exercise trials might affect the parameter estimates (Carnevale & Gaesser 1991). Although recent reports on the influence of pedal cadence on efficiency suggest that the increases in metabolic demand of higher cadences are balanced by decreases in fatigue resulting from reduced pedal forces (Widrick et al. 1992), Carnevale and

Gaesser (1991) demonstrated that estimates of CP were lower when the high-intensity trials were performed at 100 revolutions/min (rpm) than at 60 rpm. In the study, 4 predicting trials were performed at each pedal cadence. The exercise ranged from 2 to 6 minutes in the 60 rpm tests, and 2 to 4 minutes in the 100 rpm tests. While CP estimates were 15.9% higher in the 100 rpm trials, AWC estimates were not different (not statistically significant but 12.5% higher) at 100 rpm than at 60 rpm. The tendency for a decrease in AWC estimates at the higher rpm was not addressed. SEE of the parameter estimates were higher in 5 of the 7 participants at 100 rpm, further evidence of the effect of pedal cadence on the power-time relationship.

Laboratories have been criticised for selecting a cadence of, for example, 70 rpm and terminating the tests when the cadence dropped below 55 rpm (Poole 1986). However, individuals experienced with constant-power tests recognise that the drop in cadence at the end of a test is precipitous, the overestimation of work performed is slight, and the overestimation is relatively constant between exercise trials (Bulbalian et al. 1986). Using electronically braked ergometers, participants should be allowed to select a cadence and terminate tests when they are unable to sustain the power output with a predetermined minimal cadence (e.g. McLellan & Cheung 1992; Overend et al. 1992; Poole et al. 1990). Once fatigue causes a large drop in cadence it is matched by a proportionate increase in force per pedal stroke and results in a very rapid decline in cadence to the minimal rate. At present it is not clear that there is a single optimal pedal cadence for use in determining the parameters of the power-time relationship, nor is it known if participants will necessarily select a physiologically optimal cadence.

2.5 Suggestions for Protocols

There are many systems of nomenclature and protocols associated with the critical power concept. McLellan and Cheung (1992) have noted that 'there is a need to standardise the methodology used to estimate CP to enable the exchange of comparative data in future investigations'. It is likely that the use of many protocols will continue as investigators must balance many competing demands, such as feasibility (e.g. very few short trials, an inexpensive ergometer) and maximal accuracy (e.g. many trials, broad span of durations).

2.5.1 Number of Exercise Trials

Although it is possible to use only 2 predicting trials, when only 2 data points are used an error in either point can have a great effect on the magnitude of the parameter estimates. The greater the number of trials, the less impact there is of 1 'bad' test. However, the utility of the critical power method declines as more and more all-out predicting trials are required. Our experience suggests that 4 to 5 trials are optimal, as far as the trade-off between accuracy of parameter estimates and feasibility of testing is concerned. Some guidelines for ensuring the accuracy of parameter estimates are available and are presented in section 8 of this article.

2.5.2 Duration of Exercise Trials

If trials range from about 1 to about 10 minutes, a large proportion of the variation in the dependent variable about its mean will be explained by the fitted model; this good fit will be reported as a high R-squared (r^2). While longer trials might ensure a better fit, the attractiveness of the critical power model is certainly diminished, and its feasibility reduced, if participants are expected to perform 30-minute exercise trials. Based on the high reported goodness-of-fit of data to the various power-time models, and on the good relationships between the parameters and aerobic and anaerobic criterion measures, relatively short predicting trials (between 1 and 10 minutes) can be used successfully to derive the parameter estimates.

2.5.3 Repeating Trials

Because of the relatively low reliability of the AWC estimate and the learning effect on the CP estimate, the use of 2 sets of exercise trials may be warranted when accuracy of the parameter estimates is important. However, this will detract from the feasibility of the critical power concept for evaluating aerobic or anaerobic fitness. An alternative approach is to repeat the longer trials, those in which the greatest learning effect is likely to be evidenced.

3. *Validity of Critical Power as an Estimate of Maximal Sustainable Power*

In theory, the CP parameter provides an estimate of the power output that can be sustained 'for a very long time without fatigue' (Monod & Scherrer 1965) or almost indefinitely (Moritani et al. 1981), and it represents 'an inherent characteristic of the aerobic energy supply system' (Gaesser & Wilson 1988). There have been several studies designed to evaluate the validity of the CP estimate as maximal sustainable power and to elucidate the factors underlying this calculated parameter. The results of these studies follow.

3.1 Comparison of Critical Power with Other Aerobic Indicators

Critical power has been compared with the anaerobic threshold and the fatigue threshold in several studies. The fatigue threshold was identified from electromyographic data and the anaerobic threshold was determined using a variety of different protocols and criteria. In this section, studies are grouped according to the criteria by which the anaerobic or fatigue threshold was determined. No attempt is made to interpret the meaning of the fatigue threshold or the anaerobic threshold or to argue their validity.

3.1.1 Comparison of Critical Power with the Lactate Threshold

Housh et al. (1991a) reported data from a subset of the 32 individuals who participated in the study by deVries et al. (1987). CP was derived as the slope of the regression of work against time, using data from 2 all-out exercise bouts. The mean CP (230W) was significantly higher (28%) than the mean power output associated with the lactate anaerobic threshold (180W), although the 2 measures were moderately correlated (r = 0.62).

McLellan and Cheung (1992) derived parameter estimates using the power-1/time model and data from 14 men who performed 5 all-out trials. The mean value for critical power (265W) was 13% higher than the mean individual anaerobic threshold (235W).

3.1.2 Comparison of Critical Power with the Ventilatory Anaerobic Threshold

In an early study, CP was reported to be approximately the same power output as that associated with the anaerobic threshold. Moritani et al. (1981) found that CP was not significantly higher than the anaerobic threshold in 8 men and not significantly lower in 8 women. The authors reported a high correlation between the 2 variables (r = 0.92).

Results of recent studies have suggested that CP is higher than the power output associated with the ventilatory anaerobic threshold. Poole et al. (1988) derived parameter estimates in 8 men using the power-1/time model and the results of at least 5 predicting trials. The mean of the CP estimates (197W) was 64% higher than the mean ventilatory anaerobic threshold value (120W). Similar results were reported by Talbert and colleagues (1991) who found that mean CP (171W) was 16% higher than the ventilatory anaerobic threshold (147W) in 15 volunteers; the correlation between the 2 measurements was 0.82.

3.1.3 Comparison of Critical Power with the Fatigue Threshold

deVries et al. (1982) have reported high correlations between the CP estimates and the threshold for muscular fatigue identified using integrated electromyograms. Using data from the Moritani et al. (1981) study, deVries et al. (1982) found the power output associated with fatigue (187W) was no different than the CP (170W), and the 2 variables were highly correlated (r = 0.87). In a later study, deVries et al. (1987) reported that the fatigue threshold (237W) and CP (230W) were not so strongly correlated (r = 0.67).

3.2 Responses to Exercise at Critical Power

Several investigators proposed that comparison of CP against a threshold did not provide sufficient evidence to accept or reject the validity of CP as a sustainable power or as an index of endurance. Therefore, in several studies participants were monitored during prolonged exercise at their estimated CP.

3.2.1 Exercise Limited to 24 or 30 Minutes Duration

Poole et al. (1988) reported that all participants could complete 24 minutes of exercise at CP. Unfortunately, all tests were arbitrarily terminated at 24 minutes (the maximum time that the metabolic equipment could record data). The authors noted that since a steady-state $\dot{V}O_2$ was attained this should 'allow the performance of prolonged exercise'.

Jenkins and Quigley (1990) estimated CP in 8 trained male cyclists, using the linear work-time model. Work rates for the predicting trials were the same for all participants (360, 425, 480, and 520W), so there was a wide spread of times: e.g. 1 cyclist could sustain the lightest predicting power output for less than 2.5 minutes, while another cyclist was able to sustain the highest power output for more than 2.5 minutes. These investigators reported that only 2 of the 8 cyclists could sustain exercise at CP for 30 minutes without fatigue. For the other 6 cyclists, the work rate had to be reduced so that they could complete 30 minutes of exercise. All the cyclists had an elevated blood lactate level during the last 20 minutes of the exercise; the average value was 8.9 mmol/L.

McLellan and Cheung (1992) had 14 men attempt to sustain CP for 30 minutes. Only 1 succeeded. The average time to exhaustion was 20.5 minutes and the shortest time recorded was 12 minutes. Mean blood lactate in the men who completed 15 minutes was 6.8 mmol/L at that time. McLellan and Cheung (1992) concluded that methods used to measure CP overestimate the metabolic rate associated with a maximal steady-state blood lactate response.

Overend et al. (1992) evaluated the critical power concept in 12 men 71 years of age and 13 men 23 years of age. All succeeded in exercising for 24 minutes at CP. Although all the men indicated that they could continue, blood lactate levels in the young men were 8.1 mmol/L and still rising at the 24-minute mark, and were 6.5 mmol/L in the older men.

3.2.2 Exercise Limited to 60 or 90 Minutes Duration

Housh et al. (1989) estimated CP in 14 males and then directed them to exercise for as long as possible (or for 1 hour) at that power output. Mean time to exhaustion was only 33 minutes. The times ranged from 18 to 60 minutes. 3 tests were terminated at 60 minutes, although the men could have continued. It was concluded that the calculated CP exceeded by 17% the power that could actually be sustained for 1 hour.

Scarborough et al. (1991) estimated CP using the nonlinear power-time model and the results of 5 trials. Participants exercised for as long as possible (or for 90 minutes). They performed this all-out test at CP on 2 separate occasions. Mean time to exhaustion in the first test was 43 minutes (range 14.75 to 90 minutes), and in the second attempt, 51 minutes (range 24.80 to 90 minutes). They commented that, as in the Housh et al. (1989) study, there was considerable interindividual variability in the time to exhaustion at CP.

3.2.3 Exercise with No Time Limit

In a follow-up to the Scarborough and colleagues (1991) study, 8 participants were directed to exercise for as long as possible at CP; no other end-point, such as 60 or 90 minutes, was provided (Hill et al. 1991). Again, participants exercised at CP on 2 separate occasions. In the first test, the mean time to exhaustion was 51.3 minutes, and in the second test it was 65.0 minutes, an improvement of 27%.

3.3 Summary

In theory, the CP parameter provides an estimate of the power output that can be sustained 'for a very long time without fatigue' (Monod & Scherrer 1965) or 'theoretically almost indefinitely' (Moritani et al. 1981). However, since CP estimates are above the anaerobic threshold (Housh et al. 1991a; McLellan & Cheung 1992; Poole et al. 1988; Talbert et al. 1991), and given the rate of lactate production during exercise at CP (Jenkins & Quigley 1990; McLellan & Cheung 1992; Overend et al. 1992), it appears that exercise at this intensity cannot be sustained without fatigue.

In studies in which participants were directed to exercise for 24 or 30 minutes, the mean time to exhaustion was 24 minutes (Overend et al. 1992; Poole et al. 1988) or else most participants were unable to complete 30 minutes (Jenkins & Quigley 1990; McLellan & Cheung 1992). When participants were directed to exercise to exhaustion or 60 minutes, the mean exercise time was 33 minutes (Housh et al. 1989). When exercise was to exhaustion or 90 minutes, the mean times were 43 minutes (first try) or 51 minutes (second try) [Scarborough et al. 1991]. With exercise for as long as possible, the mean times were 51 minutes (first try) or 65 minutes (second try) [Hill et al. 1991]. It would seem that the suggestion of an end-point might influence participants' response. It also appears that performance at critical power is subject to a learning effect. Performance may also be affected by pedal cadence, test end-points, training status, relative anaerobic threshold (e.g. as a percentage of $\dot{V}O_{2max}$), or muscle fibre type distribution.

CP is above the anaerobic threshold, and exercise at CP cannot be sustained forever. Nevertheless, information about responses to exercise at CP, including the time to exhaustion, can contribute to the understanding of this parameter. Given the learning effect, which is manifested by almost every study participant, it is suggested that studies designed to evaluate responses to exercise at CP should include at least 2 tests.

4. Validity of the Anaerobic Work Capacity Parameter

The second parameter of the power-time relationship, AWC, provides a measure of the anaerobic capacity of the individual. Monod and Scherrer (1965) described AWC as the muscle energy reserve and Moritani and colleagues (1981) noted that the AWC estimates were unaffected when the trials were performed while individuals breathed a hypoxic gas mixture.

4.1 Comparison with Wingate Tests

The validity of AWC as anaerobic capacity has been evaluated in 3 studies based on comparison with work performed in a 30-second Wingate anaerobic test (Bar-Or 1987). The Wingate test is commonly used to assess anaerobic capability. It is easy to administer, and requires only a fast-loading mechanically-braked ergometer and a method for counting pedal revolutions accurately. Furthermore, normative data are available (e.g. Maud & Shultz 1989; Serresse et al. 1989). However, on theoretical grounds, the validity of a 30-second test has been challenged (Vandewalle et al. 1987). The test is too brief to tap the glycolytic system completely (Katch et al. 1977) and a considerable amount of anaerobic energy is still available at the conclusion of the test (Vandewalle et al. 1989). Conversely, the measured work is inflated because of the aerobic contribution during the test – this aerobic work may represent 9 to 28% (Hill & Smith 1991; Kavanagh & Jacobs 1988; Serresse et al. 1988) of the work performed.

Nebelsick-Gullett et al. (1988) reported that AWC derived from the work-time relationship in 25 young women was a valid estimate of anaerobic capacity based on its correlation with the work performed in a 30-second Wingate test ($r = 0.74$). They noted that there was a greater than 20% difference in the mean values for the 2 measures.

Vandewalle et al. (1989) also reported that AWC estimated from the work-time relationship and from work performed in 30 seconds were related ($r = 0.69$). However, despite results which were similar to those of Nebelsick-Gullett et al. (1988), these authors questioned the validity of AWC as an estimate of anaerobic capacity. They also questioned the validity of Wingate 30-second work capacity itself as an estimate of anaerobic capacity.

Jenkins and Quigley (1991) reported that, in an unpublished study, they had observed a correlation of 0.65 between AWC and work performed by trained cyclists in a 30-second Wingate test. However, no significant correlation was found between AWC and work performed by 15 volunteers of 'mixed' training status.

Results of these studies suggest that AWC is related to the amount of work performed in a Wingate test, a test that has a significant anaerobic component. However, with questions about the validity of the criterion for anaerobic capacity, namely work performed in a 30-second Wingate test, it would be premature to draw conclusions about the validity of AWC as anaerobic capacity.

4.2 Comparison with Work Capacity Tests

Jenkins and Quigley (1991) evaluated AWC as an estimate of anaerobic capacity with a comparison of total work performed during 5 bouts of 1-minute maximal exercise. This test was devised to elicit the greatest possible involvement of glycogenolysis. AWC estimates were derived in 8 men who performed 3 all-out cycling predicting trials at fixed power outputs, all in the same day. Discontinuous exercise work capacity was assessed as the total amount of work performed in 5 1-minute bouts of exercise separated by 5-minute recovery periods; exercise was all-out against a resistance reported to be 0.075 N/kg. There was a good correlation ($r = 0.74$) between the mean AWC (15.3kJ) and the total work in the discontinuous protocol (130.9kJ). The authors noted that comparison of AWC with work in a Wingate test could be misleading because of the aerobic contribution to the Wingate test. It could also be argued that there would be a considerable aerobic contribution to 5 1-minute tasks, each performed against a lower resistance than that encountered in a Wingate test, and that their correlation was no better than those reported by Nebelsick-Gullett et al. (1988) and Vandewalle et al. (1989). While the results again demonstrate a relationship between AWC estimates and performance on other tests that have a significant anaerobic component, the criterion in this study was not anaerobic capacity but, as the authors noted, the ability to perform intermittent high-intensity work.

4.3 Comparison with Oxygen Deficit

Maximal oxygen deficit has been proposed by Medbø et al. (1988) and Vandewalle et al. (1987, 1989) to be the most theoretically acceptable measure of anaerobic capacity. Despite the fact that oxygen deficit is reported in units of oxygen uptake, the value of the oxygen deficit is calculated based on a work : oxygen relationship and, therefore, does provide a work capacity (assuming that there is no change in the work : oxygen relationship).

Jenkins and Quigley (1991) reported that, in an unpublished study, they had observed no significant correlation ($r = 0.16$) between AWC and maximal oxygen deficit. Hill and Smith (1993) derived values for individual AWC in 13 men and 13 women using the nonlinear power-time model and data from 2 sets of 5 all-out predicting trials, with each trial performed on a separate day. The criterion measure for anaerobic capacity was maximal oxygen deficit. For the women, mean values for AWC (179 J/kg) were within 1% of the mean values for oxygen deficit (177 J/kg), but only moderately correlated ($r = 0.55$); for the men, mean values were within 5%, 224 and 235 J/kg, respectively, and more highly correlated ($r = 0.78$). Even the correlation for the men is hardly better than those reported between AWC and the results of other anaerobic tests. However, when comparisons between AWC and oxygen deficit are restricted to individuals whose AWC estimates are independent of the mathematical model used in their derivation (see section 8.2) the correlation improves considerably (Hill et al. 1993).

4.4 Summary

The AWC estimate derived from the power-time relationship is related to several indicators of anaerobic capacity. Establishing the validity of the parameter as anaerobic capacity is difficult, since there is not consensus acceptance of a standard for anaerobic capacity (Vandewalle et al. 1987). AWC is correlated with, but greater than, work performed in a 30-second test (Nebelsick-Gullett et al. 1988; Vandewalle et al. 1989); it is correlated with, but much less than, work performed in 5 all-out 1-minute exercise bouts (Jenkins & Quigley 1991). Estimates of AWC are correlated with, and not different from, maximal oxygen deficit (Hill & Smith 1993). It is suggested that AWC does provide a measure of anaerobic capacity, and is related to the ability to perform high-intensity exercise.

5. Response of Parameter Estimates to Training

Several studies have investigated the effect of short duration training programmes on the response of the parameters of the power-time relationship. Endurance type training would be expected to increase the value of the CP parameter, and high-intensity training would be expected to increase the value of the AWC parameter.

Gaesser and Wilson (1988) derived CP and AWC parameter estimates using the power-1/time model. The 11 men were divided into discontinuous training and continuous training groups. Training was carried out 3 days per week for 6 weeks; the training was in the form of stationary cycling, either 10 2-minute bouts at 100% $\dot{V}O_{2peak}$ ($n = 6$) or 40 minutes at 50% $\dot{V}O_{2peak}$ ($n = 5$). CP increased 15% after discontinuous training and 13% after continuous training, with improvements in all individuals. Mean AWC was not statistically different after training.

Poole et al. (1990) evaluated the effect of training on parameter estimates using methods and participants described in their previous study (Poole et al. 1988). Training was carried out 3 days per week for 7 weeks except in 2 participants who trained for only 3 and 4 weeks, respectively; the training was in the form of stationary cycling, 10 2-minute bouts at 105% $\dot{V}O_{2peak}$. CP increased in all 8 participants, with a mean improvement of 10%, from 197 to 217W. Oxygen uptake at CP increased 15%, and maximal oxygen uptake increased 15%, but the increases were not significantly correlated ($r = 0.52$). AWC was unchanged, with increases of 4 to 32% in 4 participants, decreases of 5 to 19% in 3, and no change in another.

Jenkins and Quigley (1990) have provided indirect evidence of the response of both CP and AWC to training. Mean CP and AWC in their 8 trained cyclists were 314W and 18.0kJ, respectively, while mean values for their 9 moderately active physical education students were 251 W and 15.3kJ, respectively (Jenkins & Quigley 1991). They have recently completed 2 training studies, each using an experimental design with a control group, one to evaluate the effects of high-intensity training on parameters of the power-time relationship and one to evaluate the effects of endurance training.

The purpose of the first study was to assess the effects of endurance training (Jenkins & Quigley 1992). 12 males trained for 30 to 40 minutes per session, 3 days per week for 8 weeks. Training was at an intensity at or near their calculated CP. Before and after the training period, parameters of the power-time relationship were derived using the work-time model and data collected in 3 all-out predicting trials performed at 270, 330, and 390W before training and 300, 348, and 396W (or 330, 372, and 414W, for 2 fitter males) after training. These predicting trials were separated by 3-hour recovery periods. Control individuals used the pretraining power outputs during post-training tests. Training resulted in a 30% increase in CP. There was a 7% increase in maximal oxygen uptake, but the increases in CP and maximal oxygen uptake were not significantly correlated ($r = 0.32$).

The purpose of the second study was to evaluate the effects of high-intensity training (Jenkins & Quigley 1993). 8 males performed training sessions that required 5 all-out 1-minute cycling exercise bouts against 0.736 N/kg, separated by 5-minute recovery periods. Training was carried out 3 days per week for 8 weeks. Before and after the training period, parameters of the power-time relationship were derived using the work-time model and data collected in 3 all-out predicting trials performed at 300, 348, and 396W. These predicting trials were separated by 3-hour recovery periods. Analysis of covariance techniques revealed a 49% increase in AWC, from 13.4 to 20.0kJ; there was no change in CP.

These studies suggest that the parameter estimates do respond to specific types of training. AWC is increased after high-intensity 'anaerobic' training and CP is increased after endurance training.

6. Other Exercise Modes

Although the early work of Monod and Scherrer (1965) used single-muscle exercise, most research of the critical power concept has involved exercise performed on the cycle ergometer. Aerobic and anaerobic fitness determined using a cycle ergometer protocol may not be directly related to performance of other modes of exercise. To satisfy the need for specificity in testing, the critical power concept would have to be used with data generated using the exercise mode to which the results would be applied.

The critical power model was applied to treadmill running by Hughson et al. (1984). They had runners perform exhaustive treadmill running at 6 different velocities, and used the power-time model (with velocity substituted for power) to generate estimates of parameters akin to CP and AWC. They reported that there was a good fit of the data points to the model in all participants, and the fatigue threshold (similar to CP) was correlated with maximal oxygen uptake ($r = 0.84$). The model was used to predict race times for 10 000m races: although predicted and actual times were correlated, the predicted times were about 2 to 3 minutes faster than the actual times.

Hopkins and colleagues (1989) applied the critical concept to treadmill running but used a variety of treadmill slopes at a constant speed, rather than a variety of speeds at 0% slope to characterise the power-time relationship. They used the nonlinear power-time model to derive estimates of parameters similar to CP and AWC. They reported a correlation between the inclination at which running would theoretically be sustained forever (akin to CP) and maximal oxygen uptake of 0.81, and a correlation between the inclination corresponding to a time of zero (AWC) and peak 5-second power in a Wingate test of 0.75.

Housh et al. (1991b) evaluated the responses to exercise at the fatigue threshold (akin to CP) derived in 10 males using the velocity-1/time model, as did Hughson et al. (1984), and the results of 4 all-out treadmill runs at 0% grade at velocities individually selected to result in exhaustion after 2 to 12 minutes. It was reported that the individuals' running data fitted the model well, and the fatigue threshold (or critical velocity, akin to CP) was correlated with $\dot{V}O_{2max}$. Results obtained using a different mathematical model (power curve analysis) suggested that the individuals would be able to sustain exercise at the fatigue threshold for only 9.6 to 16.8 minutes.

Pepper et al. (1992) performed a similar evaluation of the critical power concept applied to treadmill running. Parameters of the distance-time relationship were derived for 10 males based on the results of 4 all-out treadmill runs. Times were then predicted for a variety of treadmill velocities, at, above, and below the derived critical velocity. Participants exercised to exhaustion at the various velocities. Results showed that the estimated critical velocity greatly exceeded the velocity that could be sustained for an hour. Only 8 of 10 males could sustain 85% of critical velocity for 60 minutes. While use of the critical power concept allowed accurate estimation of time to exhaustion for high intensity exercise (i.e. with exhaustion occurring in less than 10 minutes), predicted times for lower velocities were grossly overestimated. Thus, results of this study supported the conclusions of Housh et al. (1991) regarding the failure of the critical power model applied to running at lower velocities. However, results of both studies did demonstrate that there was little, if any, difference between the velocity at $\dot{V}O_{2max}$ and critical velocity and that the 2 velocities were correlated [$r = 0.86$ (Housh et al. 1991b); $r = 0.81$ (Pepper et al. 1992)].

Housh and colleagues (1992) evaluated the relationship between anaerobic running capacity and peak plasma lactate. The anaerobic running capacity was determined in 12 males using the distance-time model based on the results of 4 all-out treadmill runs at 0% grade at velocities selected to result in exhaustion after 2 to 12 minutes. Plasma lactate levels were measured after an exhaustive treadmill run at 9% slope at velocities individually selected for each male so that exhaustion would occur in about 1 minute. Although each participant produced efforts that resulted in an excellent fit of the data to a distance-time model, the anaerobic running capacity and the peak lactate levels were not correlated ($r = -0.06$). It was concluded that the anaerobic running capacity derived from the treadmill tests did not provide an indicator of anaerobic capabilities.

Ginn and Mackinnon (1989) presented data obtained during kayak ergometry. CP and the maximal power output associated with a steady-state in blood lactate concentration were similar (495W and 490W) and significantly higher than the power output associated with the onset of blood lactate accumulation (341W). They observed that the critical power concept could be applied to kayak ergometry data to generate useful information about fitness and appropriate training intensity.

Wakayoshi et al. (1992) applied the critical power concept to flume swimming. Using the work-time model (with distance substituted for work) and data from all-out swims at 1.7, 1.6, 1.5, 1.4, 1.3, and 1.2 m/sec, estimates of critical velocity and anaerobic capacity, with units of metres, were generated. There was an excellent fit of the data to the linear model. Critical velocity was related to swimming velocity at the onset of blood lactate accumulation ($r = 0.95$), to swimming velocity in an all-out 400m swim ($r = 0.87$) and to oxygen uptake at the ventilatory threshold ($r = 0.82$). Recently, this group has reported that critical velocity determined from 2 all-out swims was correlated with velocity at the onset of blood lactate accumulation ($r = 0.98$) and with velocity in an all-out 400m swim ($r = 0.94$) [Wakayoshi et al. 1993]. The authors concluded that the critical power concept could be of value to coaches and athletes in assessing aerobic fitness, especially since it can be applied to data obtained from free swimming in a pool without the need for a swimming flume.

Therefore, several studies have investigated the application of the critical power concept to other modalities, and it seems that the critical power concept can be extended to outdoor or treadmill running, to ergometer kayaking, and to flume or pool swimming. While the concept has proven useful in predicting time to exhaustion (albeit within a limited range of durations), and in generating parameter estimates that are related to traditional estimates of aerobic fitness or anaerobic fitness, considerable research is still necessary to evaluate the application of the critical power concept to these other modalities and to determine the range of exercise intensities over which the velocity-time relationship is essentially hyperbolic. Use of the concept would be attractive not only because there is no need for invasive testing but also because it will permit generation of sport-specific estimates of aerobic and anaerobic fitness.

7. *Theoretical Shortcomings of the Models*

The critical power concept presumes a hyperbolic relationship between power output and time to exhaustion, a relationship described by Kennelly (1906) for racing animals, Hill (1925) for world records for a variety of forms of human locomotion, and Henry (1955) for world running records. However, there is a limit to the power that can be produced for even a very short period of time, and there is a limit to the time that even the lowest power output can be sustained – the power-time relationship is not truly hyperbolic. The hyperbolic model, in any of its 3 forms, does describe the relationship well if extremes of power output are avoided and power outputs that result in fatigue in longer than *about* 1 minute but in less than *about* 40 minutes are selected (the actual range of exercise intensities may be quite individual). If individuals exercise to exhaustion at lower power outputs, the actual time to exhaustion will be less than would be predicted based on extrapolation of the results of shorter tests. In this case, the data would no longer fit the hyperbolic model in any of its 3 forms: in the nonlinear power-time model, the data point would fall below the projected curve (or to the left of the asymptote); in the work-time model, the point would fall below (to the right) of the projected line; and in the power-1/time model, the point would fall below the projected line.

As discussed in section 3, CP cannot be sustained forever. The hyperbolic model describes power-time data over a limited range of power outputs and times. Therefore, derivation of parameters of the power-time relationship using the critical power concept must be limited to a range of data for which the relationship is essentially hyperbolic (that is, for which the power-time relationship is hyperbolic and the work-time and power-1/time relationships are linear). Parameters derived from the power-time relationship may then be used not only to describe aerobic and anaerobic fitness but to predict time to exhaustion for given power outputs (but only if that power output is within the range for which the power-time relationship is essentially hyperbolic). The models cannot be applied to extremely high power outputs (which cannot be attained or can be sustained only a few seconds) or low power outputs.

Other models have been proposed that may better describe the relationship between power (or velocity) and time. For example, Péronnet and Thibault (1989) have provided a model that accurately predicts world running records. It is a modification of the hyperbolic model that addresses 4 flaws in the hyperbolic model upon which the critical power concept is based.

Essentially, the critical power model, where power = (AWC/time) + CP, assumes that a given power output (i.e. CP) can be sustained by aerobic energy sources independent of the duration of exercise; it also assumes that the anaerobic capacity or muscle energy stores (AWC) can be fully tapped and 'spread out' over time, independent of the duration of exercise. The model of Péronnet and Thibault (1989) model considers: (1) that energy from glycolysis is not available at its maximal rate at the onset of exercise – there is a delay in the response of glycolysis; (2) that the total energy available from glycolysis declines in exercise bouts of over about 15 minutes; (3) that energy from aerobic metabolism is not available at the maximal rate at the onset of exercise – there is a delay in the response of the aerobic system as well; and (4) that the percentage of the maximal oxygen uptake that can be sustained declines slightly as the duration of exercise increases. The above points 1 and 3 affect short term exercise. Points 2 and 4 explain why the critical power parameter overestimates maximal sustainable power. The critical power concept assumes that anaerobic capacity is available regardless of the duration of exercise and that a fixed percentage of maximal oxygen uptake is available regardless of the duration of exercise.

Theoretically, the model proposed by Péronnet and Thibault (1989) should be superior to the critical power model. It describes a power-time relationship in which the power continues to decline as time increases. It would predict a finite time to exhaustion for any power output, even those below CP, and therefore would appear to provide a better description of the power-time relationship, especially during prolonged exercise. The model has been verified only with data from 13 elite athletes, and there are drawbacks when it comes to application: (1) it estimates mechanical power (or racing velocity) from availability of energy and requires assumptions about efficiency; (2) it requires data from at least 4 bouts of exercise, 3 of which have to be under 420 seconds and 1 (or more) of which must be considerably longer; and (3) calculations require a complicated FORTRAN programme.

The critical power concept must be used with the understanding that exercise trials are within the range of times for which the power-time relationship is essentially hyperbolic. The hyperbolic relationship fails to hold at very high or very low power outputs. Despite this shortcoming, the critical power concept is easy to understand, simple to apply and provides meaningful information about aerobic and anaerobic fitness. The derived CP parameter cannot be expected to be sustained without fatigue. Understanding the limitations of the critical power model should enhance application of the concept.

8. Enhancing the Validity of the Parameter Estimates

The critical power concept can provide useful information. But sometimes the information generated by critical power testing can be confusing. For example in the Jenkins and Quigley study (1992) involving evaluation of the effects of endurance training, there was an apparent, but not statistically significant, 26% decrease in the estimate of the AWC parameter, from 19.9 to 14.7kJ. The authors noted that times to exhaustion at the highest predicting power output (396W) were not reduced by training. With no change in performance time at 396W, it is difficult to conceive that there was a decrease in anaerobic capacity and no reason to expect any change in AWC; moreover, there is no physiological explanation for the tendencies of the control group to have higher CP (215 versus 226W) and lower AWC (16.8 versus 12.9kJ) during the second set of trials. Logically, either pre-training AWC estimates were inflated or post-training AWC was underestimated; a lower pre-training value would have been more reasonable, considering that these were untrained men who had pre-training AWC essentially equal to the 20.0kJ attained after 8 weeks of intense training in their other training study (Jenkins & Quigley 1993).

Gaesser and Wilson (1988) reported similar results. AWC estimates were not significantly reduced after training designed to increase CP; but the authors noted that, while CP was increased in every participant, the response of AWC to training was variable, with individuals who demonstrated the greatest increase in CP generally exhibiting the greatest decrease in AWC. It is not the intent of this review to question the effect of endurance training on CP; however, it should be noted that it has been our experience that trials at the lower intensities tend to be subject to a greater learning effect than trials at the higher intensities (see also Poole et al. 1988), and this could lead to an inflation of pre-training AWC estimates, an underestimation of pre-training CP estimates, and an overestimation of the effect of training on CP.

It is the purpose of this review to caution the reader that there is variability in performance during predicting trials (Poole et al. 1988), in AWC estimates from 1 set of trials to the next (Gaesser & Wilson 1988; Smith & Hill 1993), and in AWC estimates derived before and after periods of *endurance* training (Gaesser & Wilson 1988; Jenkins & Quigley 1992; Poole et al. 1990). There is disagreement between investigators in the time that CP can be sustained, for example, between 20 minutes (McLellan & Cheung 1992) and over 60 minutes (Hill et al. 1991; Housh et al. 1989). These results suggest that either different protocols are measuring different things and labelling them CP and AWC, or that CP and AWC have little real value. We assume that the parameters do have value, and the following sections provide ways to ensure, improve, or at least evaluate the accuracy of the parameter estimates.

8.1 Standard Error of the Parameter Estimates

Many investigators provide the SEE associated with the computer-generated CP and AWC estimates. Low SEE reflect a high fit of the data to the model. We have recently evaluated the validity of AWC estimates as anaerobic by comparison with oxygen deficit and found that the accuracy of AWC estimates can be ensured by using estimates only when the SEE falls within certain guidelines (Hill et al. 1993). Since the SEE may be reduced by selecting predicting trials for which there is a small range of power outputs (that is, if the r^2 is not decreased), further research is necessary to evaluate whether these guidelines are specific to the range of power outputs (3.5 to 6.5 W/kg for women and 4.0 to 8.5 W/kg for men) and resulting times to exhaustion used in the study. The results suggested that, regardless of the mathematical model that is selected, AWC estimates are more accurate measures of anaerobic capacity when the associated SEEs are low. Specifically, for the nonlinear power-time and linear work-time models, AWC is an acceptable measure of anaerobic capacity when the SEE is <10% of AWC; for the linear power-1/time model, AWC is an acceptable measure of anaerobic capacity when the SEE is <5% of AWC.

8.2 Variability among Estimates Generated by the Models

In most studies, when data are collected and used to generate parameter estimates, one of the 3 mathematical models is selected. In theory, it should not matter which model is selected, if the power-time points are within the range in which the power-time relationship is essentially hyperbolic, in which case the power-1/time and work-time relationships will be linear.

It has been argued that the nonlinear power-time model is appropriate for extraction of the parameters and that different models give different estimates (Gaesser et al. 1990). However, in a study with 47 participants, Smith and Hill (1992) found no difference in estimates generated using the 3 models, and it has been suggested that the existence of differences between estimates derived using the 3 different models can be taken as evidence that there is a systematic error in the predicting data or that the data points are outside of the range for which the power-time relationship is hyperbolic. It has also been reported that when variability of AWC estimates is low, all estimates are acceptable measures of anaerobic capacity, but when variability is high, only the nonlinear estimate is close (Hill et al. 1993). Thus, when the facilities (i.e. personal computer and statistical package capable of performing linear and nonlinear regression) are available, and when at least 3 predicting trials are performed, comparison of estimates generated by the 3 models can give some insight into the accuracy of the estimates.

8.3 Number of Trials

The number of predicting trials required is largely a function of the motivation for testing and the degree of accuracy that is needed. Feasibility, in terms of number and duration of trials and demands on both the participants and investigators, must be balanced against the need to estimate the CP and AWC parameters accurately.

Housh et al. (1990) have reported that the practicality of the critical power test can be improved by using only 2 carefully selected predicting trials: in their study, a subset of 2 trials provided estimates of AWC and CP similar to the estimates generated from 4 predicting trials. In some studies, only 2 trials have been used (deVries et al. 1987; Housh et al. 1991a). However, Housh et al. (1990) pointed out that 2 trials must be carefully selected and that an error in the time for one or both of the power loadings would have substantial effects on the estimates of the parameters.

Poole et al. (1988) have reported on the variability in performance at any given power output, and Poole (1986) suggested that at least 4 or 5 predicting trials are required to allow precise identification of the parameters. Gaesser and Wilson (1988), Nebelsick-Gullett et al. (1988) and Smith and Hill (1993) have reported lower test-retest correlations for AWC than for CP. Gaesser and Wilson (1988) and Smith and Hill (1993) have reported a learning effect in the estimate of the CP parameter estimate from 1 set of 5 predicting trials to the next. Based on the results of these studies, it would seem that repeated sets of predicting trials would be necessary to improve the accuracy of the parameter estimates.

Thus, suggestions for a suitable number of predicting trials range from 2 to 2 sets of 5. The decision must be based on the nature of the study and the proposed use of the data, and on other factors such as the fitness of the participants and their familiarity with truly all-out exercise. If only 2 trials are performed, the investigator has no information about the fit of the data to the model, since 2 points describe a straight line with a zero SEE. If at least 3 trials are performed, then the criteria described above in sections 8.1 and 8.2 can be applied: the investigator can be confident that there is a good fit of the data to the hyperbolic model, in whatever form the model may be presented. Alternatively, data points can be visually inspected for evidence of under-achievement in one particular trial. However, the investigator cannot be sure if performance was maximal and if subsequent changes in parameter estimates are contaminated by a learning effect.

If 2 or more trials are performed and then repeated, performance in the predicting trials can be compared with evidence of a learning effect and the estimates of CP and AWC can be compared for evidence of an effect of learning. Comparison of the CP and AWC estimates is preferred as a learning effect may be manifested as a decrease in one parameter and an increase in the other because of relatively greater change at one power output than the other.

While this author favours repeated sets of predicting trials, or at least performance of some learning trials, a large number of trials or repetition of some or all trials is probably not necessary unless small changes in CP (i.e. a mean 3 to 6% learning effect) or interindividual variability in the AWC estimate (i.e. ± 0 to 15% or more) are crucial to the interpretation of the data. Moreover, large numbers of trials may be associated not only with changes in learning, but changes in motivation, and even fitness. Certainly, the more trials that are required, the less attractive use of the critical power concept becomes.

9. Conclusions

Several studies report that CP is correlated with several indicators of aerobic fitness, such as the fatigue threshold (by electromyograph), the ventilatory and lactate anaerobic thresholds, and $\dot{V}O_{2max}$, and that AWC is related to several indicators of anaerobic capacity, such as work in 30 sec, work in intermittent high-intensity exercise, and maximal oxygen deficit. CP has been shown to increase after endurance training, and AWC to increase after high-intensity training. It is concluded that the critical power concept provides a way to generate estimates that reflect aerobic fitness or endurance (CP) and anaerobic work capacity (AWC). The concept requires using only an ergometer and a stopwatch; there is no need for expensive equipment for respiratory gas analysis, for blood analysis, or for electromyography, and there is no invasive testing. Research is under way to determine whether the critical power concept can be extended to forms of ergometry other than stationary cycling, to provide sport-specific evaluation of fitness, prediction of performance, and quantification of training intensity. The major drawback to the method is that a number of all-out predicting trials is required. Individuals using the critical power concept should understand the variability associated with the derived parameter estimates, the effects of their choice of number of predicting trials and the methods that can be employed to ensure or improve the accuracy of parameter estimates. They should also appreciate the shortcomings of the hyperbolic model.

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Correspondence and reprints: Dr *David W. Hill*, Exercise Physiology Laboratory, Department of Kinesiology, PO Box 13857, University of North Texas, Denton, TX 76203-3857, USA.