*International Journal of Sports Physiology and Performance,* 2011, 6, 128-136


# Application of Critical Power in Sport

**Anni Vanhatalo, Andrew M. Jones, and Mark Burnley**

The critical power (CP) is mathematically defined as the power-asymptote of the hyperbolic relationship between power output and time-to-exhaustion. Physiologically, the CP represents the boundary between the steady-state and nonsteady state exercise intensity domains and therefore may provide a more meaningful index of performance than other well-known landmarks of aerobic fitness such as the lactate threshold and the maximal $O_2$ uptake. Despite the potential importance to sports performance, the CP is often misinterpreted as a purely mathematical construct which lacks physiological meaning and only in recent years has this concept begun to emerge as valid and useful technique for monitoring endurance fitness. This commentary defines the basic principles of the CP concept, outlines its importance to high-intensity exercise performance, and provides an overview of the current methods available for its assessment. Interventions including training, pacing and prior exercise can be used to alter the parameters of the power-time relationship. A future challenge lies in optimizing such interventions in order to positively affect the parameters of the power-time relationship and thereby enhance sports performance in specific events.

***Keywords:*** endurance training, athletic training, exercise performance, exercise physiology

The purpose of this commentary is to illustrate how the critical power (CP) concept can be applied to sports performance. Our intention is to provide a gentle introduction to an area of study that is too often unnecessarily mired in mathematical terminology and physiological jargon. Despite the potential importance to sports performance, the key practical features of the CP concept have rarely been conveyed from the scientist to the athlete and coach. We have therefore identified, wherever possible, examples from sports performance to illustrate the concepts we discuss. A comprehensive scientific review of the CP concept has recently been published,[1] and we refer readers to this review for more detailed information on the physiological and mathematical foundations of the concept. In this article we will define the CP concept; illustrate how it applies to sports performance; describe how it can be measured; address some of the issues associated with interpreting test results; and finally provide examples of how the parameters of the CP concept may be altered for the benefit of endurance sports performance.

Anni Vanhatalo and Andrew M. Jones are with Sport and Health Sciences, College of Life and Environmental Sciences, St. Luke's Campus, University of Exeter, Exeter, U.K. Mark Burnley is with the Department of Sport and Exercise Science, Aberystwyth University, Aberystwyth, U.K.

## What Is the Critical Power Concept?

The concept of a "critical" power can be viewed from two different perspectives. The first, and perhaps conceptually the easiest, is to position the CP within the exercise intensity spectrum. During incremental exercise commencing from rest and progressing to maximal exertion, the athlete will encounter "thresholds" which demarcate specific exercise intensity domains.[2] For approximately the first half of such a test, exercise will be performed in the moderate-intensity domain, ie, below the lactate threshold (LT). Once the LT is surpassed, the athlete will enter the heavy-intensity domain.[2] As the power output increases further, to around 70–90% of the power output associated with the attainment of maximal $O_2$ uptake ($VO_2max$) during incremental exercise (note that there is considerable interindividual variability in the percentage of power at $VO_2max$ associated with CP), the athlete enters the severe-intensity domain; soon after, depending on the ramp-rate and the fitness of the subject, the $VO_2max$ is attained and volitional exhaustion rapidly ensues. In the transition between the heavy- and severe-intensity domains, the athlete will traverse their CP, and consequently, for the remainder of the exercise test, she or he will be on "borrowed time" as the athlete progressively expends the "finite work capacity" that is available above CP (known as the W′). From this perspective, the CP can be defined in terms of the physiological responses to constant-power exercise performed above it (ie, non-steady state) and below it (ie, steady state). A full description of these responses is beyond the scope of this commentary but is available elsewhere.[1,3–5]

The second perspective is mathematical. From this point of view, the CP is one of two (or more[6,7]) empirical parameters that define the relationship between power output (P) and time-to-exhaustion ($T_{lim}$) within the severe-intensity domain. It is well established that this relationship is hyperbolic, with the power-asymptote representing the CP and the curvature constant termed W′ (Figure 1A):

$$T_{lim} = W'/(P - CP) \qquad \text{Equation 1}$$

The CP concept therefore provides a means of predicting the time-to-exhaustion at any power output above the CP (within the severe domain). For example, if we take a hypothetical athlete with a measured CP of 333 W and W′ of 18.35 kJ, we can calculate (using Eq. 1) the amount of time that this athlete could sustain a given power output. For example, for a power output of 360 W, $T_{lim}$ = 18,350 J / (360 – 333 W) = 680 s. It may also be useful to know which power output must be chosen in order to achieve a given time-to-exhaustion. For this purpose the hyperbolic Equation 1 is solved for P, thus giving it a linear form (Figure 1A inset):

$$P = W'/T_{lim} + CP \qquad \text{Equation 2}$$

Using the same CP and W′ as in the above example, a power output that results in exhaustion in 180 s can be calculated as $P$ = 18,350 J / 180 s + 333 W = 435 W.

Note that while the CP theoretically represents the highest power output that can be sustained without exhaustion, in practice the CP merely indicates the lower limit of the applicable range of the CP concept. Indeed, it has been reported that exercise at CP can typically not be sustained beyond approximately 30 min.[8] What the concept is *not* able to do is predict the time-to-exhaustion at or below the CP. Thus, we take the view that when the concept was originally formulated by Monod

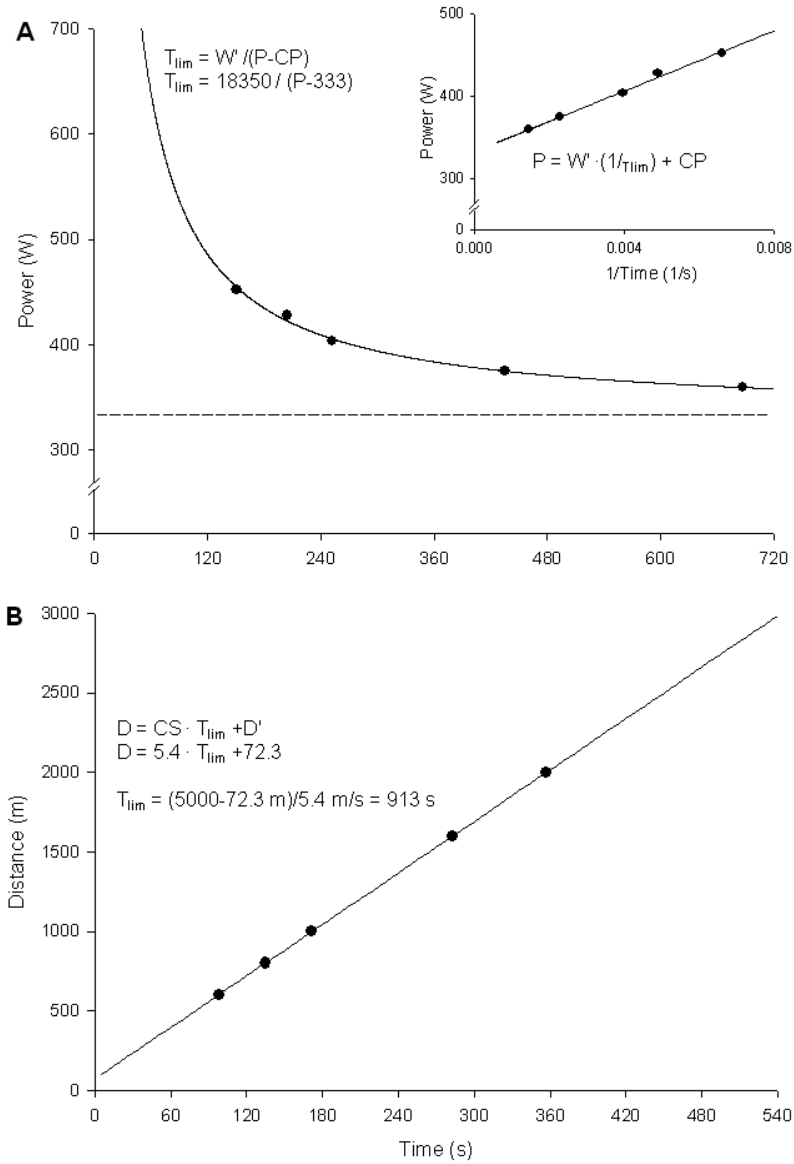


**Figure 1** — The hyperbolic power-duration relationship (Eq. 1) in an individual with a CP of 333 W and a W′ of 18.35 kJ (Panel A). The CP is given by the power-asymptote (horizontal dashed-line) and the W′ is represented by the gray rectangle which is limited by the coordinates of any data point along the P-$T_{lim}$ curve and the power-asymptote. The hyperbolic relationship can be linearized by plotting the power against the inverse of time ("1/time model") shown in the panel A inset. Panel B illustrates the linear distance-time model (Eq. 3) used to estimate the CS and D′ based on performance over five running distances from 600 to 2000 m. It can be predicted that this athlete, with a CS of 5.4 m/s and D′ of 72.3 m, would be capable of completing a 5 km race in 15 min and 13 s.

and Scherrer[9] they erred in stating that "when the dynamic work is inferior or equal to the critical power . . . exhaustion cannot occur." Suggestions that exercise at or below the CP should be sustainable for an infinite period of time may be mathematically justifiable, but this is clearly not the case in reality!

The curvature constant of the power-duration relationship, the W′, provides a measure of the fixed amount of external work that can be performed above the CP before exhaustion occurs, independent of the rate at which that work is done. The magnitude of the W′ has been suggested to be dependent upon the extent of the severe domain, ie, the difference between the CP and the $VO_2$max.[10,11] This means that endurance-trained athletes, who have high CP relative to their $VO_2$max (narrow severe domain), have only modest W′ values (typically <15 kJ in cycling), whereas sprint-trained athletes tend to have low CP relative to $VO_2$max (wide severe domain) and much higher W′ (>25 kJ). The extent of the severe domain will also dictate the magnitude of the so-called $VO_2$ "slow component," which is related to a loss of muscle contractile efficiency and is measured as a progressively increasing $O_2$ cost as severe-intensity exercise proceeds.[12] The W′ and the $VO_2$ slow component may therefore be interrelated, with both, in turn, being linked to the process of muscle fatigue.[11,12]

## To Which Sports Does the CP Concept Apply?

The CP concept is relevant in any sporting situation in which a significant period of time is spent within the severe-intensity domain, and therefore a significant energetic contribution must come from the constituents represented by W′ (thought to be predominantly "anaerobic" in nature). Although the CP concept is most commonly studied using cycle ergometry, it has also been generalized to running,[13–15] rowing,[16] swimming,[17] and continuous and intermittent isometric exercise,[9,18] where the analogs of power (eg, speed or velocity, force, torque) are substituted as appropriate. Furthermore, the CP model has been modified for intermittent exercise,[19] and thus has potential applications for interval training and team sports such as association football, rugby and hockey, for example. In fact, it is perhaps easier to list those sports in which the CP concept does *not* apply: sports activities that involve a single or only a few muscle contractions (eg, archery, field athletics); sports where the work-to-rest ratios are such that the limits set by the W′ parameter are unlikely to be seriously challenged (eg, American football, baseball, cricket); and events where the power output does not exceed CP (eg, golf, ultra-endurance events).

The CP concept has been suggested to be of most relevance to continuous activities lasting approximately 2 min to 30 min, although the concept may still be relevant for considerably longer endurance events, such as the half-marathon and marathon. A recent article has sparked debate as to who will break the 2 h barrier for the marathon.[20] It can be very simply stated that the runner responsible for achieving this feat must have a critical speed exceeding 21.1 $km \cdot h^{-1}$. The possession of a lower critical speed would mean that the athlete would be attempting to run 42.2 km within the severe-intensity domain, a clearly impossible task from a physiological perspective. Overall, the CP concept has a very broad application to sports performance but also by its nature does not apply to some sports and only indirectly influences performance in others.

## How Is the Critical Power Measured?

Although the CP and W′ reflect physiological phenomena, their measurement is fundamentally based on performance, ie, mechanical work done (or distance covered) and time. To establish these parameters, all the experimenter requires is a means of measuring external power output (or its analogs), and a stopwatch. With the advent of portable power measuring devices and GPS technology, monitoring of the power-duration relationship may also be achieved in the field with little specialist equipment and minimal data analysis.[21,22] The most common procedure for assessing the parameters of the power-duration relationship in the laboratory is by having subjects perform several (a minimum of three, but ideally four or more) constant-power exercise tests to exhaustion on separate days. The power outputs chosen are typically between 75% and 105% of the maximum power output achieved in a ramp test (although see Vanhatalo et al[23] for a more precise definition of the power outputs used), and are intended to yield times to exhaustion of between about 2 and 15 min.[24] The difference between the shortest and longest trial should be at least 5 min. Recent race or time trial performances can alternatively be used as prediction trials in the field. The resulting data can be analyzed using linear or nonlinear regression.[1,7,24] For research purposes, it is good practice to quantify the accuracy of the parameter estimates by reporting the standard error of estimate (SEE; usefully expressed as a coefficient of variation, %) or the 95% confidence intervals for each parameter, in addition to the $r^2$ for the overall fit.[24,25]

We will now describe how data collected during track running training can be used to predict the best performance time for a runner in a 5 km race. Assume that a hypothetical athlete completes 600, 800, 1000, 1600 and 2000 m distances as fast as possible on separate occasions within a 2 wk period, and the performance times are 98, 135, 171, 283 and 357 s, respectively (Figure 1B). The "critical speed" (CS; equivalent to CP) and the D′ (equivalent to W′) parameters are derived by linear regression analysis of the relationship between distance (m) and time (s):

$$D = CS \cdot T_{lim} + D' \qquad \text{Equation 3}$$

In our example y = 5.4x + 72.3, yielding CS = 5.4 m/s and D′ = 72.3 m. In order to predict performance over 5 km, Equation 3 is rearranged:

$$T_{lim} = (D - D')/CS$$
$$T_{lim} = (5000 - 72.3 \text{ m})/5.4 \text{ m/s} = 913 \text{ s} \qquad \text{Equation 4}$$

The athlete in question should therefore be capable of completing a 5 km race in 15 min and 13 s.

A major practical limitation to the assessment of the power-time relationship and the estimation of the CP and W′ in athletes has been the requirement for the completion of multiple exhaustive bouts on separate days. This makes the process arduous, time-consuming, and labor-intensive both for the athlete and the coach or physiologist. To address this, we have developed an "all-out CP test," which allows the estimation of the CP and W′ in a single cycle ergometer trial.[10,23] This test has been demonstrated to be robust and reliable and, provided that subjects are highly motivated, to provide an estimate of CP that is remarkably accurate.[10,23,26] In short, there is a range of options for the establishment of the power-duration relationship, and these protocols can be adapted to suit a variety of exercise modes both in the laboratory and in the field.

## Interventions That Alter the CP and W′

Alterations in the $VO_2$max and/or the rate at which the $VO_2$ increases during severe-intensity exercise ("$VO_2$ kinetics") may be reflected as changes in the power-duration relationship.[12] The CP can be increased by short-term (4 to 6 wk) continuous endurance training[27] and by high-intensity interval training.[10,28,29] That the CP is an important index of aerobic fitness is supported by findings that it is reduced in hypoxia and elevated in hyperoxia,[11,30] and that it correlates with other indices of aerobic fitness such as the $VO_2$max and the lactate threshold.[30]

The training-induced alterations in W′ are somewhat more complex, and indeed only one investigation has achieved a significant increase in W′ following "all-out" sprint training.[31] Conversely, training interventions that have been effective in increasing the CP have been associated with a trend for a reduction in W′ (Figure 2).[10,27] It should be noted that although a reduction in W′ reflects impaired performance in very short duration exercise bouts, the overall consequence of increased CP and reduced W′ is beneficial to endurance performance; it is well known that endurance-trained athletes make poor sprinters! After years of endurance training, athletes tend to reach the "ceiling" of their trainable $VO_2$max, but it may still be possible to improve the CP. This results in a "narrowing" of the range of power outputs that encompasses the severe domain, and is reflected in a low W′.[1,10,11]

Apart from training, the W′ may also be altered by pacing strategy and prior "warm-up" exercise, with associated changes in $VO_2$ kinetics and the $VO_2$max. A fast-start pacing strategy, which speeds the overall rate of increase in $VO_2$, has been linked to significantly greater work done above CP (ie, W′) and improved "end-sprint" performance compared with even-paced and slow-start pacing strategies during ~2 to 3 min of high-intensity exercise.[32,33] The attainment of $VO_2$max during very high-intensity exercise (~120% $VO_2$max) can be speeded by the completion of a prior bout of heavy-intensity exercise, which also tends to increase the magnitude of the W′.[34] However, it is important that both the intensity of the priming exercise bout and the subsequent recovery duration are carefully considered if the features of the power-duration relationship (and performance) are to be enhanced rather than impaired.[34–38]

## Conclusions

The CP concept provides a useful framework in which to study the physiological mechanisms underlying exercise tolerance as well as a valuable assessment tool for performance monitoring in sport. The popularity of the CP concept has been hampered by the myth that "complicated" mathematics is necessary for its assessment (in fact, simple linear regression is all that is needed); the time-consuming conventional testing protocol; and, at times, the use of theoretical jargon and inconsistent terminology. We have endeavored to make this concept more user-friendly by providing evidence for the physiological foundations of the power-time

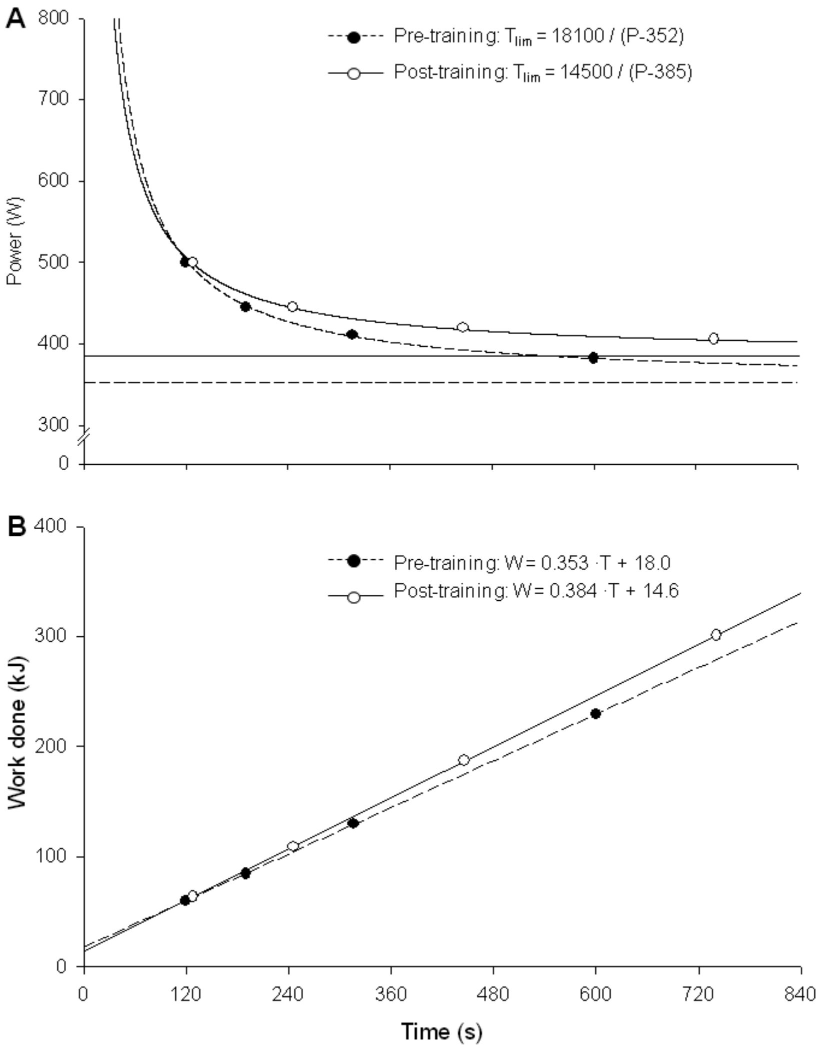


**Figure 2** — The impact of a period of high-intensity interval training on the hyperbolic power-duration curve (panel A) and the corresponding linear work-time relationship (panel B) in the same individual. Note the elevated power-asymptote (ie, increased CP) (panel A) and the lower y-intercept in panel B (ie, reduced W′) posttraining. Panel A suggests that the athlete's performance in very high-intensity bouts (>500 W) may be impaired after training; however, the ability to sustain power outputs <500 W is considerably improved.

relationship, developing a single-visit CP test, and elucidating the practical applications of the CP and W′ parameters. Future challenges lie in fully understanding the multiple and interrelated determinants of the CP and W′, in refining methods for their assessment, and in developing interventions which positively impact on the CP and/or W′ parameters and enhance sports performance.

# References

1. Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC. Critical power: implications for determination of $VO_2$max and exercise tolerance. *Med Sci Sports Exerc*. 2010;42:1876–1890.
2. Jones AM, Poole DC. Introduction to oxygen uptake kinetics and historical development of the discipline. In: Jones AM, Poole DC, eds. *Oxygen uptake Kinetics in Sport, Exercise and Medicine*. London, New York: Routledge; 2005.
3. Burnley M, Doust JH, Vanhatalo A. A 3-min all-out test to determine peak oxygen uptake and the maximal steady state. *Med Sci Sports Exerc*. 2006;38:1995–2003.
4. Jones AM, Wilkerson DP, DiMenna F, Fulford J, Poole DC. Muscle metabolic responses to exercise above and below the "critical power" assessed using $^{31}$P-MRS. *Am J Physiol Regul Integr Comp Physiol*. 2008;294:R585–R593.
5. Poole DC, Ward SA, Gardner GW, Whipp BJ. Metabolic and respiratory profile of the upper limit for prolonged exercise in man. *Ergonomics*. 1988;31:1265–1279.
6. Morton RH. A 3-parameter critical power model. *Ergonomics*. 1996;39:611–619.
7. Morton RH. The critical power and related whole-body bioenergetic models. *Eur J Appl Physiol*. 2006;96:339–354.
8. Brickley G, Doust JH, Williams CA. Physiological responses during exercise to exhaustion at critical power. *Eur J Appl Physiol*. 2002;88:146–151.
9. Monod H, Scherrer J. The work capacity of a synergic muscular group. *Ergonomics*. 1965;8:329–338.
10. Vanhatalo A, Doust JH, Burnley M. A 3-min all-out cycling test is sensitive to a change in critical power. *Med Sci Sports Exerc*. 2008;40:1693–1699.
11. Vanhatalo A, Fulford J, DiMenna FJ, Jones AM. Influence of hyperoxia on muscle metabolic responses and the power–duration relationship during severe-intensity exercise in humans: a $^{31}$P magnetic resonance spectroscopy study. *Exp Physiol*. 2010;95:528–540.
12. Burnley M, Jones AM. Oxygen uptake kinetics as a determinant of sports performance. *Eur J Sport Sci*. 2007;7:63–79.
13. Hughson RL, Orok CJ, Staudt LE. A high-velocity treadmill running test to assess endurance running potential. *Int J Sports Med*. 1984;5:23–25.
14. Kolbe T, Dennis SC, Selley E, Noakes TD, Lambert MI. The relationship between critical power and running performance. *J Sports Sci*. 1995;13:265–269.
15. Smith CGM, Jones AM. The relationship between critical velocity, maximal lactate steady-state velocity and lactate turnpoint velocity in runners. *Eur J Appl Physiol*. 2001;85:19–26.
16. Kennedy MDJ, Bell GJ. A comparison of critical velocity estimates to actual velocities in predicting simulated rowing performance. *Can J Appl Physiol*. 2000;25:223–235.
17. Wakayoshi K, Yoshida T, Udo M, et al. Does critical swimming velocity represent exercise intensity at maximal lactate steady state? *Eur J Appl Physiol*. 1993;66:90–95.
18. Burnley M. Estimation of critical torque using intermittent isometric maximal voluntary contractions of the quadriceps in humans. *J Appl Physiol*. 2009;106:975–983.
19. Morton RH, Billat LV. The critical power model for intermittent exercise. *Eur J Appl Physiol*. 2004;91:303–307.
20. Joyner MJ, Ruiz JR, Lucia A. The Two-Hour Marathon: Who and When? *J Appl Physiol*. 2010 Aug 5. [Epub ahead of print]
21. Quod MJ, Martin DT, Martin JC, Laursen PB. The power profile predicts road cycling MMP. *Int J Sports Med*. 2010;31:397–401.
22. Smith JC, Dangelmaier BS, Hill DW. Critical power is related to cycling time trial performance. *Int J Sports Med*. 1999;20:374–378.
23. Vanhatalo A, Doust JH, Burnley M. Determination of critical power using a 3-min all-out cycling test. *Med Sci Sports Exerc*. 2007;39:548–555.
24. Hill DW. The critical power concept. A review. *Sports Med*. 1993;16:237–254.

25. Hill DW, Smith JC, Leuschel JL, Chasteen SD, Miller SA. Effect of pedal cadence on parameters of the hyperbolic power-time relationship. *Int J Sports Med*. 1995;16:82–87.
26. Vanhatalo A, Doust JH, Burnley M. Robustness of a 3 min all-out cycling test to manipulations of power profile and cadence in humans. *Exp Physiol*. 2008;93:383–390.
27. Jenkins DG, Quigley BM. Endurance training enhances critical power. *Med Sci Sports Exerc*. 1992;24:1283–1289.
28. Gaesser GA, Wilson LA. Effects of continuous and interval training on the parameters of the power-endurance time relationship for high-intensity exercise. *Int J Sports Med*. 1988;9:417–421.
29. Poole DC, Ward SA, Whipp BJ. The effects of training on the metabolic and respiratory profile of high-intensity cycle ergometer exercise. *Eur J Appl Physiol*. 1990;59:421–429.
30. Moritani T, Nagata A, deVries HA, Muro M. Critical power as a measure of physical work capacity and anaerobic threshold. *Ergonomics*. 1981;24:339–350.
31. Jenkins DG, Quigley BM. The influence of high intensity exercise training on the $W_{lim}$-$T_{lim}$ relationship. *Med Sci Sports Exerc*. 1993;25:275–282.
32. Bailey SJ, Vanhatalo A, DiMenna FJ, Wilkerson DP, Jones AM. A fast-start strategy improves $\dot{V}O_2$ kinetics and high-intensity exercise performance. *Med Sci Sports Exerc*., in press.
33. Jones AM, Wilkerson DP, Vanhatalo A, Burnley M. Influence of pacing strategy on $O_2$ uptake and exercise tolerance. *Scand J Med Sci Sports*. 2008;18:615–626.
34. Jones AM, Wilkerson DP, Burnley M, Koppo K. Prior heavy exercise enhances performance during subsequent perimaximal exercise. *Med Sci Sports Exerc*. 2003;35:2085–2092.
35. Bailey SJ, Vanhatalo A, Wilkerson DP, Dimenna FJ, Jones AM. Optimizing the "priming" effect: influence of prior exercise intensity and recovery duration on $O_2$ uptake kinetics and severe-intensity exercise tolerance. *J Appl Physiol*. 2009;107:1743–1756.
36. Burnley M, Doust JH, Jones AM. Effects of prior warm-up regime on severe-intensity cycling performance. *Med Sci Sports Exerc*. 2005;37:838–845.
37. Vanhatalo A, Jones AM. Influence of prior sprint exercise on the parameters of the 'all-out critical power test' in men. *Exp Physiol*. 2009;94:255–263.
38. Ferguson C, Whipp BJ, Cathcart AJ, Rossiter HB, Turner AP, Ward SA. Effects of prior very-heavy intensity exercise on indices of aerobic function and high-intensity exercise tolerance. *J Appl Physiol.* 2007;103:812–822.