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# Critical Power: Implications for Determination of $\dot{V}O_{2\max}$ and Exercise Tolerance

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<sup>1</sup>*School of Sport and Health Sciences, St. Luke's Campus, University of Exeter, Exeter, Devon, England, UNITED KINGDOM;* <sup>2</sup>*Department of Sport and Exercise Sciences, Aberystwyth University, Aberystwyth, Ceredigion, Wales, UNITED KINGDOM;* <sup>3</sup>*Institute of Food Nutrition and Human Health, Massey University, Palmerston North, NEW ZEALAND;* and <sup>4</sup>*Departments of Kinesiology, Anatomy and Physiology, Kansas State University, Manhattan, KS*

## ABSTRACT

JONES, A. M., VANHATALO, M., BURNLEY, R. H., MORTON, R. H., and POOLE, D. C. Critical Power: Implications for Determination of  $\dot{V}O_{2\max}$  and Exercise Tolerance. *Med. Sci. Sports Exerc.*, Vol. 42, No. 10, pp. 00–00, 2010. For high-intensity muscular exercise, the time-to-exhaustion ( $t$ ) increases as a predictable and hyperbolic function of decreasing power ( $P$ ) or velocity ( $V$ ). This relationship is highly conserved across diverse species and different modes of exercise and is well described by two parameters: the “critical power” (CP or CV), which is the asymptote for power or velocity, and the curvature constant ( $W'$ ) of the relationship such that  $t = W'/(P - CP)$ . CP represents the highest rate of energy transduction (oxidative ATP production,  $\dot{V}O_2$ ) that can be sustained without continuously drawing on the energy store  $W'$  (composed in part of anaerobic energy sources and expressed in kilojoules). The limit of tolerance (time  $t$ ) occurs when  $W'$  is depleted. The CP concept constitutes a practical framework in which to explore mechanisms of fatigue and help resolve crucial questions regarding the plasticity of exercise performance and muscular systems physiology. This brief review presents the practical and theoretical foundations for the CP concept, explores rigorous alternative mathematical approaches, and highlights exciting new evidence regarding its mechanistic bases and its broad applicability to human athletic performance. **Key Words:** FATIGUE, EXERCISE INTENSITY DOMAINS,  $\dot{V}O_2$  KINETICS, ANAEROBIC CAPACITY, ATHLETIC PERFORMANCE, MAGNETIC RESONANCE SPECTROSCOPY

It is a common experience that running, cycling, or swimming at a relatively fast yet comfortable pace can be continued for a considerable period without undue fatigue. However, even slightly increasing the pace substantially increases the perceived effort and dramatically reduces the tolerable duration of exercise. It is perhaps less well appreciated that these experiences have solid mathematical and physiological bases, which are enshrined in the critical power (CP) concept. The CP thus represents an important parameter of aerobic function (in addition to gas exchange threshold (GET), maximal  $O_2$  uptake ( $\dot{V}O_{2\max}$ ), and exercise efficiency) and one that provides an invaluable framework in which to study and understand more fully the mechanisms of fatigue and exercise intolerance. It is only relatively recently that some of the key features of the con-

cept have come to light, although the concept has been studied, in one form or another, since the scientific investigation of exercise began.

This review builds on the historical foundations of the CP concept (Historical bases for the critical power concept section) to provide essential perspectives for the reader to appreciate the importance of contemporary discoveries and relevance to human (and animal) muscular performance. Two key problems that have hampered a broader implementation and interpretation of the CP concept have been overcome in very recent investigations and are the focus of the sections on Mechanistic bases of the critical power concept and Application of the critical power concept to all-out exercise. Specifically, lack of knowledge regarding specific intramyocyte fatigue mechanisms operant during high-intensity (severe) exercise above the CP (Mechanistic bases of the critical power concept section) and the cumbersome nature of the multiple fatiguing tests thought to be requisite for defining the power–time-to-exhaustion (i.e.,  $P-t$ ) relation and extracting the parameters CP and  $W'$  (Application of the critical power concept to all-out exercise section). The Mathematical features of the critical power concept section places the two-parameter  $P-t$  model in its mathematical perspective and addresses whether a more complex three-parameter model is justifiable theoretically and practically. Crucially, this section investigates optimal race strategies from a mathematical orientation, which leads

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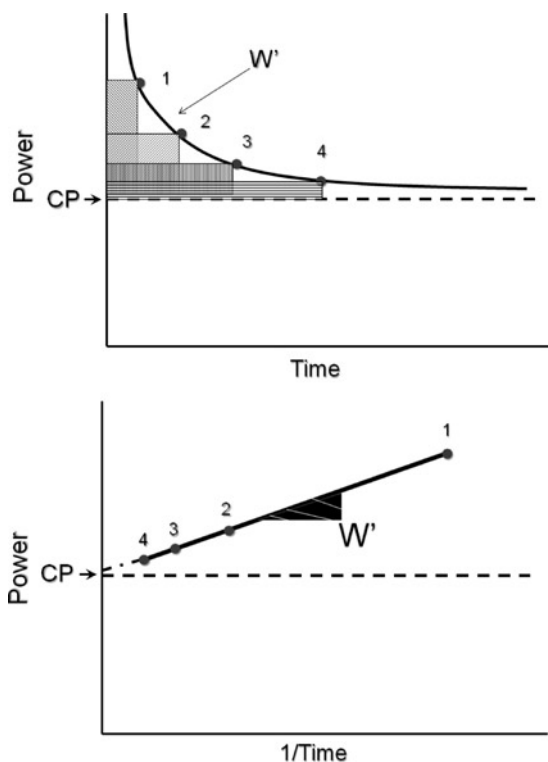
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appropriately into the final section where practical applications of the CP concept are explored more fully (Practical applications of the critical power concept section).

## HISTORICAL BASES FOR THE CRITICAL POWER CONCEPT

**F1** It can be no overstatement that the history of human physical endeavor has been shaped and constrained by the  $P-t$  relationship (Fig. 1). Across millennia, the performance of soldiers, laborers, and elite athletes locomoting over land, in water, and, more recently, in flight has been bounded by the CP and  $W'$  parameters. For example, the Roman military genius Vegetius, writing more than two millennia ago, presents evidence that legionaries were required to march for several hours at the military step (2.85 mph, 4.6 km·h<sup>-1</sup>) carrying 43.25 lb (19.6 kg) (51,81). Whipp et al. (80,81) have estimated that this required sustaining a metabolic rate somewhere between 1.4 and 1.7 L of O<sub>2</sub>·min<sup>-1</sup>. As the penalty for failure to reach this objective was death, the military step had to be set below the CP (or CV) of most legionaries to avoid crippling the ranks and eroding morale. That the Roman military was arguably the finest mobile fighting force in the world for several centuries implies that the military step was not positioned too far below CP (CV).



**FIGURE 1**—*Top panel:* Schematic showing the power–time ( $P-t$ ) relationship for high-intensity exercise. Notice that although it has become customary to illustrate the nonlinear model using reversed axes,  $t$  remains the dependent variable. *Bottom panel:* Determination of parameters CP and  $W'$  from the linear  $P - 1/t$  transform.

In more contemporary times, the English physiologist A. V. Hill conflated his observations in contracting isolated frog muscles with those of exercising humans in an attempt to understand the physiological determinants of extraordinary physical performance and muscle fatigue. This led to his construction of velocity–time curves, similar to that schematized in Figure 1, from world records for runners, swimmers, rowers, and cyclists (29) (see also Hill [30]). It is pertinent that current (2009) world records also fit velocity–time curves similar to those of Hill (29). Central to Hill (and Otto Meyerhoff), winning the 1922 Nobel prize was his demonstration that both aerobic and anaerobic energy sources were recruited to power high-intensity muscle contractions (see Bassett [3] for review). It is fitting, therefore, that our present understanding of the  $P-t$  relationship is founded on the compartmentalization and coordinated function of these two energy sources.

In 1965, Monod and Scherrer (54) defined the CP of a muscle (or muscular group) as “the maximum rate (of work) that it can keep up for a very long time without fatigue.” They considered both dynamic work and isometric exercise and extracted the two parameters, CP and a finite amount of work performable above CP (“energy store” component, later termed  $W'$ ), by plotting total work done (abscissa) against time-to-exhaustion (ordinate) for multiple fatiguing exercise bouts. Linear regression for the points yielded an intercept that corresponded to  $W'$ , and CP was given by the slope of the parallel line displaced downward to project from the origin. By studying continuous and intermittent isometric contractions and noting the improved performance on the latter, Monod and Scherrer (54) considered CP to be dependent, in part, on muscle blood flow and hence O<sub>2</sub> delivery. Subsequent experiments (see below) have demonstrated unequivocally that CP is determined by oxidative function and that  $W'$  can be manipulated independently, for example, by altering muscle phosphocreatine (PCr) stores, consistent with its dependence on finite anaerobic energy sources (52,53,65,74).

Because of the functional significance of CP, its position relative to other signatory parameters of aerobic function—the so-called “anaerobic threshold” (now more appropriately termed the GET or lactate threshold (LT) and  $\dot{V}O_{2max}$ —is of great importance. In the early 1980s, two contrasting viewpoints held that CP was placed at apparently widely divergent locations. Specifically, the brilliant physiologist Douglas R. Wilkie (83), whose interests included the feasibility of man-powered flight (eventually realized by Bryan L. Allen’s epic crossing of the English Channel in the Gossamer Albatross in 1979), formulated an equation that situated CP at a power output somewhere above  $\dot{V}O_{2max}$ . In marked contrast, Moritani et al. (55) placed CP at a much lower  $\dot{V}O_2$  not different from that at the “anaerobic threshold” (considered by those authors to be synonymous with LT or GET). Obviously, these two notions are mutually exclusive, and resolution of this crucial issue rests on a combination of theoretical modeling and experimental

physiological approaches that characterized gas exchange and metabolic behaviors near CP as detailed below.

Wilkie's formulation was a valiant attempt to bring together mechanical and physiological determinants of high-intensity exercise tolerance:

$$P = E + A/t - E\tau(1 - \exp^{-t/\tau}) \quad [1.1]$$

where  $P$  is a constant-power output that designates CP,  $E$  is the power at  $\dot{V}O_{2max}$ ,  $A$  is work available from anaerobic energy sources (notionally synonymous with  $W'$ ),  $t$  is elapsed time, and  $\tau$  is a  $\dot{V}O_2$  time constant of 10 s (13,83). Despite ostensibly providing a close fit to some data sets, this equation errs dramatically: it places CP at a power output above  $\dot{V}O_{2max}$  and presumes the same very rapid  $\tau$  for all work rates and individuals. The disparity between the  $\tau$  of 10 s selected by Wilkie and the 25–40 s measured in young healthy subjects was attributed to time delays incurred between  $\dot{V}O_2$  in the muscle and its (then) site of measurement via pulmonary gas exchange (83). It is now known that  $\tau \dot{V}O_2$  approaches 10 s only in a select few cases; certain elite athletes such as Paula Radcliffe, the women's marathon world record holder (44), some cyclists (47), and horses (49). However, in most individuals, it is far slower and, when the transit time between muscle and mouth is accounted for (~10–20 s),  $\tau$  at the mouth faithfully represents that at the exercising muscle, is far longer than 10 s, and is quite variable among individuals (26,48). Moreover, it has been well established that constant-power outputs that engender  $\dot{V}O_{2max}$  are sustainable only for a relatively short period (35,64).

At the other end of the spectrum, the conclusion of Moritani et al. (55) that the CP is located at a  $\dot{V}O_2$  that is correlated with, and not different from, the  $\dot{V}O_2$  at the "anaerobic threshold," LT, or GET must be challenged on the basis of more recent evidence. Specifically, although CP is correlated with the LT or GET, it is clear that the CP occurs at a substantially higher metabolic rate (and thus, power output) at least in non-highly trained individuals (64,65). However, it is pertinent that the metabolic rate (i.e.,  $\dot{V}O_2$ ) difference between GET/LT and CP becomes compressed in very fit individuals (44) such that, in these individuals, GET/LT and CP lie in closer proximity, but with CP always at the higher  $\dot{V}O_2$ . In summary, refinements in data collection and modeling have demonstrated beyond any reasonable doubt that the CP is a distinct and meaningful parameter, not simply an alternative to maximal oxygen uptake or the GET/LT. Its determination, however, remains a challenge to the experimental physiologist (see Application of the critical power concept to all-out exercise section).

In 1982, Whipp et al. (78) used a simple two-parameter hyperbolic fit to the power–time relation:

$$(P - CP)t = W' \quad [1.2]$$

which may be transformed into its linear formulation

$$P = (W'/t) + CP \quad [1.3]$$

The power–time ( $P-t$ ) curves were constructed using data obtained from four or more independent high-intensity constant-power exercise bouts for which the tolerable duration was 2–15 min (64). Higher-power outputs that were predicted to induce exhaustion in <2 min were expressly avoided because of concerns that constraints related to mechanical power generation might become apparent. Similarly, far lower power outputs, where the subject would not fatigue until >15–20 min and which would likely entail a greater motivational component, were not used to determine CP and  $W'$ .

Poole et al. (64) used this hyperbolic analysis to characterize empirically the physiological response to exercise performed near CP in a cohort of healthy, physically active, but not highly trained, young men. The CP was found to occur at ~80%  $\dot{V}O_{2max}$ , approximately midway between GET and  $\dot{V}O_{2max}$  (Fig. 2). Accepting a margin of determination imprecision, this represented the highest power output (or, more correctly, metabolic rate) (2) at which  $\dot{V}O_2$  and blood [lactate] could be stabilized. Specifically, at CP, the profile of  $\dot{V}O_2$  demonstrated a pronounced slow-component rise that was superimposed on the rapid initial "fundamental" increase (Fig. 3). However, after several minutes or more at CP, the  $\dot{V}O_2$  leveled off as did blood [lactate] that increased from resting values (~1 mM) to stabilize at 5–6 mM on average. In marked contrast, exercise at a power output just 5% above CP induced a completely different metabolic response:  $\dot{V}O_2$  rose inexorably to  $\dot{V}O_{2max}$  and blood [lactate] increased systematically until the subject was unable to continue the exercise task (Fig. 3). Figure 4 demonstrates that, for just an incrementally small increase in power output above CP,  $\dot{V}O_2$  may increase (via the  $\dot{V}O_2$  slow component) by a liter or more (22,64). The CP therefore presents the upper boundary of the heavy exercise intensity domain and the lower boundary of the severe-intensity exercise domain in which all power outputs lead to  $\dot{V}O_{2max}$ , and the tolerable duration of work

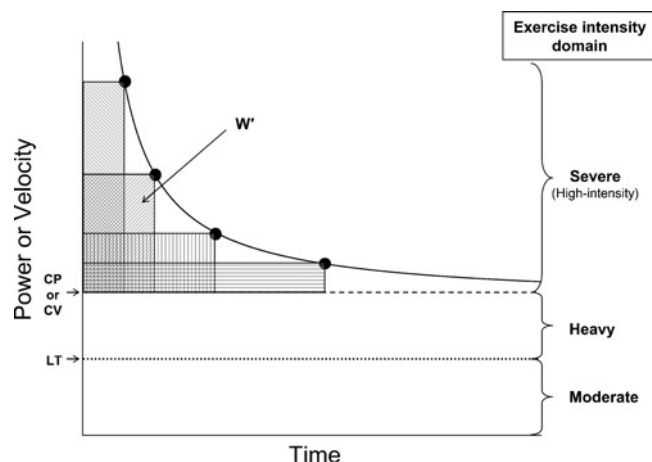
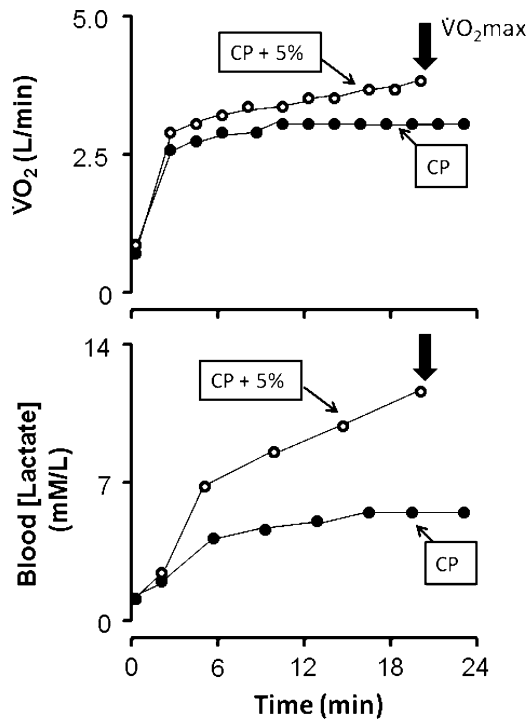


FIGURE 2—Schematic of the power–time ( $P-t$ ) relationship for high-intensity exercise illustrating the location of the LT (synonymous with the GET) relative to CP for healthy, physically active young men.



**FIGURE 3**—Group mean oxygen uptake ( $\dot{V}O_2$ ) (*top panel*) and blood [lactate] (*bottom panel*) responses ( $n = 8$ ) to constant-power exercise at CP (*solid symbols*) and 5% above CP (*open symbols*). *Arrows* denote point of fatigue for CP + 5% bout; note achievement of  $\dot{V}O_{2max}$ . For exercise at CP,  $\dot{V}O_2$  and blood lactate both stabilized, and the bout was stopped at 24 min without fatigue. SE bars were omitted for clarity. See text for more details. Used with permission from Poole et al. (64).

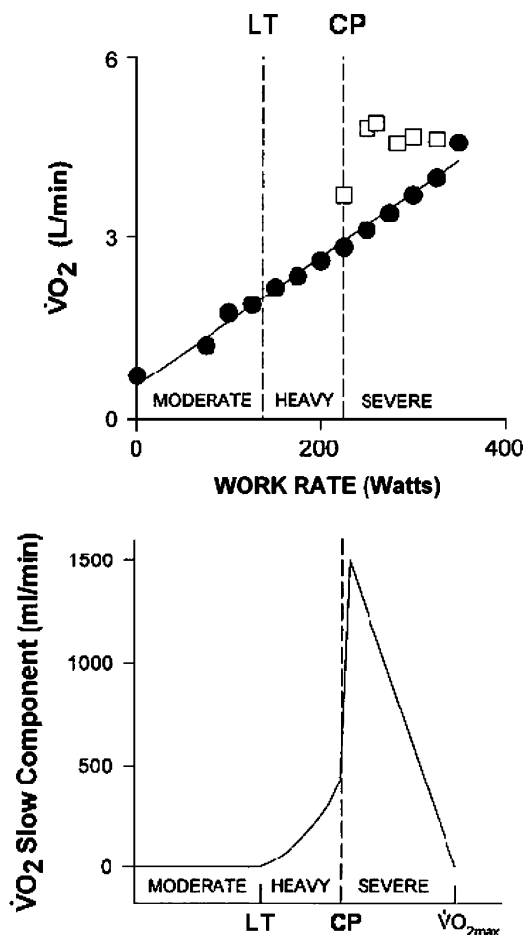
is highly predictable from the  $P-t$  relationship (Figs. 1 and 2). In deference to Wilkie, note from Figure 4 that, whereas CP cannot be above the power output corresponding to  $\dot{V}O_{2max}$ , when the slow-component increase in  $\dot{V}O_2$  is allowed to run its course and elevate  $\dot{V}O_2$  to  $\dot{V}O_{2max}$ , work rates only incrementally above CP result in the achievement of  $\dot{V}O_{2max}$ .

To date, the essential characteristics of the  $P-t$  relationship (and its parameters CP and  $W'$ ) describe exercise tolerance for locomotory activity across many species including salamander (20), mouse (5), and horse (50), as well as for different muscle contraction protocols (e.g., isometric [54] and isotonic [42]) and exercise modes (running [19,37], cycling [28,31,32,63–66,68,70,82], swimming [77], and rowing [33]) in humans. Thus, as will be demonstrated more fully below, the highly conserved hyperbolic  $P-t$  relationship, its mechanistic underpinnings, and tight coherence with systemic responses ( $\dot{V}O_2$  and blood [lactate]) and muscle metabolism support its key role in defining muscular performance in its broadest context.

## MECHANISTIC BASES OF THE CRITICAL POWER CONCEPT

As developed above, the  $P-t$  relationship is defined by two constants: the power-asymptote known as the CP and the curvature constant  $W'$ . The  $W'$  (J) indicates the maxi-

imum amount of work that can be performed  $>CP$  so that the magnitude of this work capacity remains the same regardless of the chosen work rate  $>CP$  (Fig. 1, top panel). The CP has been defined as the highest sustainable rate of aerobic metabolism (31,54,55) that occurs at a similar work rate to the so-called maximal lactate steady state (66). According to the classic interpretation, the  $W'$  (sometimes inaccurately called the “anaerobic work capacity”) comprises the energy derived through substrate-level phosphorylation using PCr and glycogen, with an additional small aerobic contribution from myoglobin- and (venous) hemoglobin-bound  $O_2$  stores (15,52–55). However, the precise physiological underpinnings of the  $P-t$  relationship are challenging to address experimentally and have been the subject of some controversy.



**FIGURE 4**—*Top panel*: Oxygen uptake ( $\dot{V}O_2$ )/work rate relationship for incremental exercise (*solid symbols*), where work rate is increased by  $25 \text{ W}\cdot\text{min}^{-1}$  to fatigue and  $\dot{V}O_2$  was achieved during constant-power exercise (*open symbols*) for one healthy subject. The *leftmost open symbol* is at critical power (CP), which denotes the highest power output at which  $\dot{V}O_2$  can be stabilized (see Fig. 3). All other *five open symbols* denote that  $\dot{V}O_{2max}$  is achieved in response to constant-power exercise even when the power output is far below the maximum achieved on the incremental test (i.e., CP + 5%). *Bottom panel*: Schematic illustrating the extraordinary size of the  $\dot{V}O_2$  slow component necessary to achieve  $\dot{V}O_{2max}$  at a power output just above CP (i.e., at the lower end of the severe-intensity exercise domain). On the basis of data from Poole et al. (64).



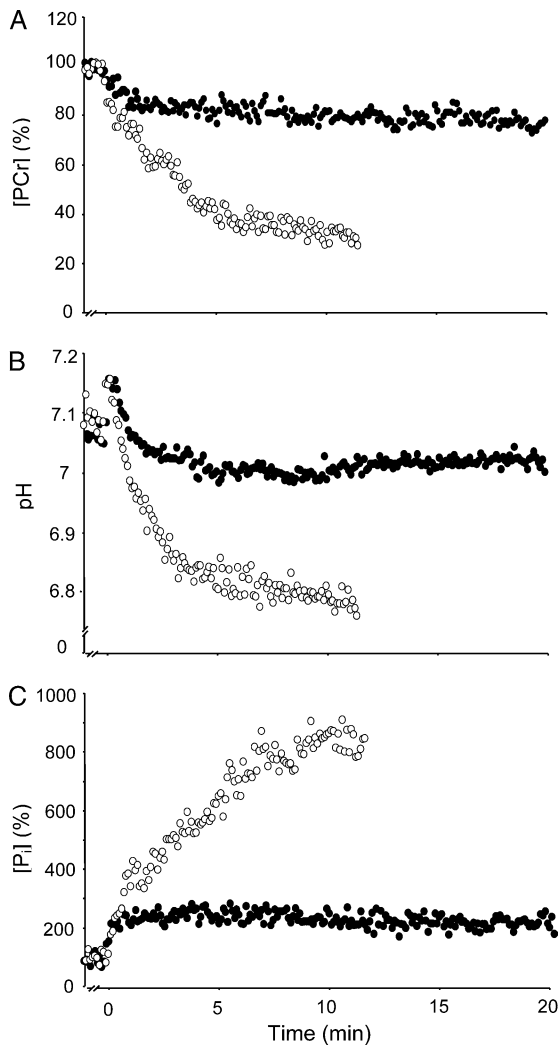
It is pertinent to note that the  $P$ - $t$  parameters differ from any physiological index of fitness in that they are based on the measurement of *performance* as  $t$  (i.e., time-to-exhaustion) and on the externally measured mechanical work done (per unit time) rather than the behavior of any single physiological variable, such as blood lactate concentration or pulmonary  $\dot{V}O_2$ . In other words, given the multifaceted nature of fatigue during high-intensity exercise (1,18), any one solitary physiological index is unlikely to entirely account for the  $W'$  or the CP. The complex mechanistic bases of the  $P$ - $t$  relationship have been elucidated by various interventions used to manipulate individually the CP and  $W'$ . Specifically, it has been established that the CP increases after short-term continuous endurance training (38) and after high-intensity interval training (23,65,72) and may be reduced when exercise is performed in hypoxia (55). The  $W'$  is reduced after previous high-intensity (>CP) exercise (17,28,74) and by glycogen depletion (53) and can be increased by short-term sprint-interval training (39). In addition, there is some evidence that the  $W'$  may be enhanced by dietary creatine loading (52,69) (see also Eckerson et al. [16] and Vanhatalo and Jones [75]) and by previous heavy-intensity exercise (41).  $W'$  also tends to decrease after training interventions that increase the CP (38,72). Interpretation of these results is challenging because of the complex and interrelated physiological nature of CP and  $W'$ ; thus, an intervention aimed specifically at manipulating the CP might also affect the  $W'$  and *vice versa*. Considering that some of the metabolites associated with “anaerobic” energy transfer (which have been thought to be related to the  $W'$ ) act as signaling mechanisms to stimulate mitochondrial respiration (which defines the CP), it is clear that the classic interpretation of CP and  $W'$  as distinct aerobic and anaerobic parameters, respectively, is overly simplistic.

The severe-intensity exercise domain, which defines the applicable range of the  $P$ - $t$  relationship, is characterized by two unique predictable features: at exhaustion, the  $\dot{V}O_2$  will equal  $\dot{V}O_{2\max}$  and the amount of external work done in excess of CP will equal  $W'$  (35,64,82). The characterization of  $W'$  as a fixed anaerobic energy reserve (54,55), which is primarily determined by the available intramuscular PCr and glycogen stores (e.g., Ferguson et al. [17] and Jones et al. [42]), is now gradually becoming redefined. It is acknowledged that the magnitude of the  $W'$  might also be attributed to the accumulation of fatigue-related metabolites, such as  $H^+$  and  $P_i$  and extracellular  $K^+$  (18), which occurs in concert with the depletion of intramuscular PCr and glycogen. It has been postulated further that the  $W'$  is intrinsically related to the development of the  $\dot{V}O_2$  slow component, which is truncated ultimately at  $\dot{V}O_{2\max}$  (10,17,41). That the intramuscular [PCr] follows similar kinetics to pulmonary  $O_2$  during exercise (67), thereby exhibiting an intensity domain-specific behavior (42), suggests that the  $P$ - $t$  relationship may be intrinsically linked to muscle metabolic and respiratory control processes within the severe-intensity exercise domain. Below, we discuss two recent studies that were the first to

investigate the muscle metabolic underpinnings of the  $P$ - $t$  relationship.

The Historical bases for the critical power concept section described the landmark study by Poole et al. (64), which established the CP as the demarcation between the heavy- and severe-intensity exercise domains, with distinct pulmonary gas exchange and blood acid-base profiles above and below CP (Fig. 3). Whether a metabolic steady state is attained or not has important implications for the development of muscular fatigue and exercise intolerance. However, the mechanistic bases of the CP boundary at the level of the contracting muscle were only recently addressed systematically. The contention that the  $P$ - $t$  relation was defined by muscle energetics seemed reasonable given that the two-parameter CP model had originally been established for small muscle group exercise (54). Jones et al. (42) examined this contention using  $^{31}P$  magnetic resonance spectroscopy ( $^{31}P$  MRS). The hypothesis that the intramuscular [PCr] and associated phosphate-linked regulators of oxidative metabolism would exhibit the same intensity domain-specific behavior near the CP as the established systemic responses was tested (64). During separate knee extension exercise trials performed 10% below (20 min in duration) and 10% above (to exhaustion) CP, the intramuscular [PCr],  $[P_i]$ , and pH were monitored using  $^{31}P$  MRS. All subjects completed 20 min of heavy exercise at 10% below CP without undue exertion, and steady-state responses in [PCr] (~68% of baseline), pH (~7.01), and  $[P_i]$  (~314% of baseline) were attained within 1–3 min at levels, indicating only moderate metabolic perturbation (Fig. 5). In contrast, when exercise was performed 10% above CP, within the severe-intensity exercise domain, the limit of tolerance was reached after  $14.7 \pm 7.1$  min. The [PCr] and pH fell progressively with time reaching ~26% of resting values and ~6.87, respectively, at exhaustion, and the  $[P_i]$  increased to ~564% above baseline (Fig. 5). These findings established the CP as a boundary above which intramuscular [PCr],  $[P_i]$ , and pH cannot be stabilized. The distinct responses recorded above and below CP within a very narrow range of work rates (CP  $\pm 2$  W) demonstrate the existence of a critical threshold at CP for muscle metabolic control beyond (i.e., above) which a physiological steady state is unattainable.

The study by Jones et al. (42) demonstrated that the intramuscular [PCr] and pH continued to decrease until the limit of tolerance when exercise was performed at a work rate slightly above CP. It had been speculated that the predictable exercise tolerance above CP may reflect the rate of decrease in some intramuscular fatigue-inducing factor or factors toward some “low, limiting value” and that these factors may include [PCr] and/or pH (64). However, Jones et al. (42) did not resolve whether these variables would reach the same low values at exhaustion at different work rates within the severe-intensity exercise domain. Such behavior, if present, would resemble the consistent attainment of pulmonary  $\dot{V}O_{2\max}$  at fatigue in the severe-intensity exercise domain irrespective of the work rate (35,64). Inspiration of



**FIGURE 5**—Muscle [PCr] (A), pH (B), and [Pi] (C) responses to <CP (solid circle) and >CP (open circle) knee extension exercise in a representative subject. [PCr] and [Pi] data are expressed as percentage change from resting baseline. Redrawn from Jones et al. (42).

hyperoxic gas during exercise is associated with a reduced [PCr] slow component and improved high-intensity exercise tolerance (27). Surprisingly, only one study has addressed the consequences of manipulating the inspired O<sub>2</sub> fraction on the *P*–*t* relationship: in a limited sample of two subjects, hyperoxia was shown to reduce the CP with no consistent effect on the *W*' (55). In a recent study, Vanhatalo et al. (73) therefore tested the hypotheses that hyperoxia would increase the “aerobic” CP parameter without changing the *W*' and that intramuscular [PCr] and pH would reach the same low, possibly limiting, values at exhaustion during exercise at different work rates within the severe-intensity exercise domain.

Using exhaustive single-leg knee extension bouts at four different exercise intensities above CP, the *P*–*t* relation was determined in normoxia (i.e., 0.21 O<sub>2</sub>) and hyperoxia (0.70 O<sub>2</sub>, balance N<sub>2</sub>) (73). Using <sup>31</sup>P MRS, [PCr] (~5%–10% of resting baseline) and pH (~6.65) values measured at the limit of tolerance were not significantly different ei-

ther among the different work rates or with different inspired O<sub>2</sub> fractions. Rather, consistent with CP being a parameter of oxidative function, hyperoxia increased CP (normoxia = 16.1 ± 2.6, hyperoxia = 18.0 ± 2.3 W, *P* < 0.05), thereby extending the time-to-exhaustion (in trials lasting longer than ~4 min) and reducing the rate at which [PCr] and pH decreased with time. Surprisingly, however, hyperoxia served to reduce *W*' (1.92 ± 0.70 vs 1.48 ± 0.31 kJ, *P* < 0.05) such that there was an inverse correlation between changes in CP and *W*' (*r* = –0.88)—a finding that contradicts the classic definition of the *W*' parameter as a fixed anaerobic energy reserve (73). Exercise training is also associated with a similar mutual interdependency between CP and *W*' (72), which may be attributed to the relative changes induced by a given intervention on the CP (the lower boundary of the severe-intensity exercise domain) and the  $\dot{V}O_{2max}$ , resulting in a change in the range of work rates that encompass the severe-intensity exercise domain (10). These recent findings indicate that the *W*' may not represent a fixed “anaerobic” substrate store, *per se*, but rather a mechanical work capacity that can be used while [PCr] and pH project toward a nadir value, which occurs near  $\dot{V}O_{2max}$  and ultimately exhaustion (35,64). It is important to note that the limit of tolerance in severe exercise might occur when a particular intramuscular environment is achieved (36), of which the [PCr] and pH measured in this study should be regarded as only two of many possible indicators.

Collectively, these recent MRS investigations have extended our knowledge of the mechanistic bases of the *P*–*t* relationship. Specifically, it is now known that CP represents a critical threshold for intramuscular metabolic control, above which exhaustive exercise results in the attainment of consistently low end-exercise pH and [PCr] values irrespective of the chosen work rate within the severe-intensity exercise domain. This *P*–*t* relationship therefore encompasses a specific range of high-intensity work rates where exercise induces a predictable and inexorable progression of increasing intramuscular metabolic perturbation, which ultimately limits exercise tolerance. The *P*–*t* relationship may therefore be regarded as an inherent characteristic of muscle bioenergetics.

## APPLICATION OF THE CRITICAL POWER CONCEPT TO ALL-OUT EXERCISE

Despite the physiological significance of the CP concept and its broad applicability across exercise modes and species (see Historical bases for the critical power concept section for references), estimation of its parameters is not routine during either physiological research or diagnostic exercise testing. We believe that the primary reason for this is that the cumbersome nature of the repeated fatiguing exercise bouts required for CP and *W*' resolution has limited its wider application. In contrast, the incremental exercise test that permits extraction of several key aerobic parameters

(i.e., GET/LT,  $\dot{V}O_{2\max}$ , efficiency) in a single procedure has become almost ubiquitous in exercise testing facilities. To address this problem, recent investigations have explored the potential of using prolonged all-out exercise to determine CP and  $W'$  in a single test.

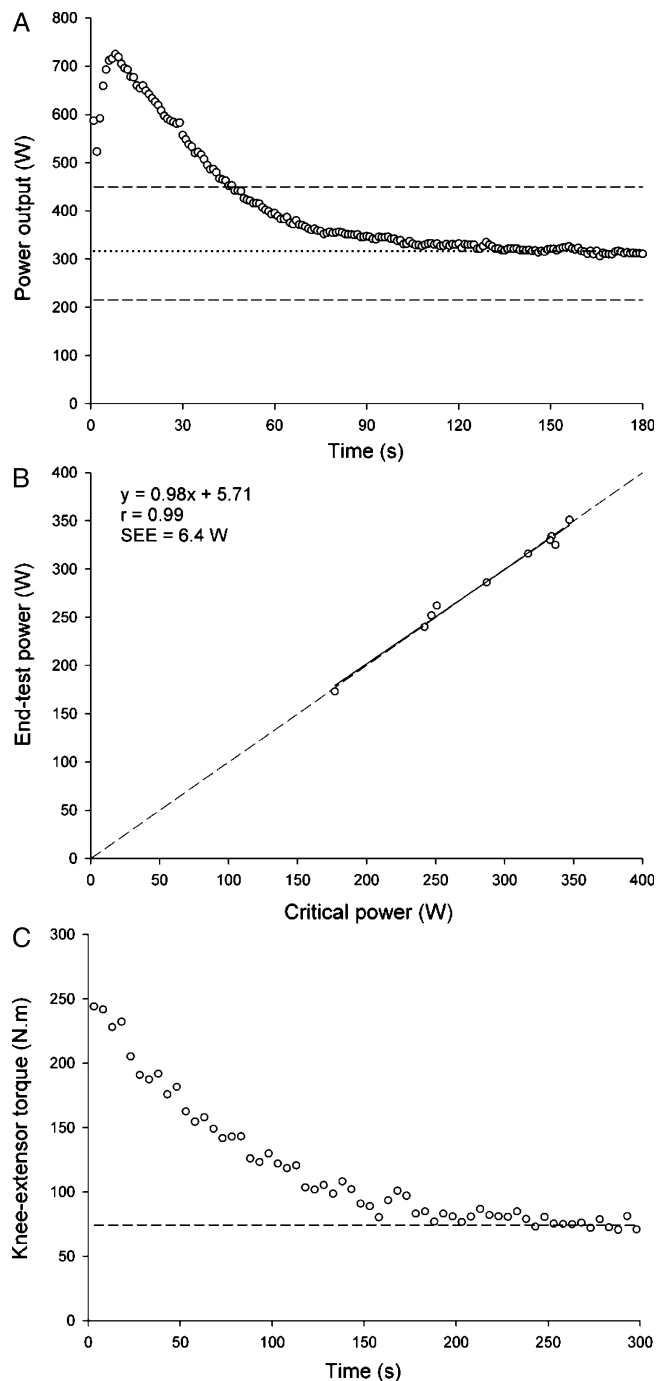
All-out cycle exercise bouts of 30 s (Wingate test) and up to 90 s (12,25) have been used to measure maximal power output and to estimate the so-called “anaerobic capacity” and accumulated  $O_2$  deficit. During these all-out tests, power output typically falls to less than 50% of its initial/peak value, which is well below the power output at  $\dot{V}O_{2\max}$  measured during fast-ramp incremental exercise protocols (12,14). Although these tests were too short to determine CP (7), a potential link between all-out exercise and CP was suggested (7,14). However, these investigations begged two crucial questions: 1) If all-out exercise continued beyond 90 s, would power output eventually stabilize? 2) As the theoretical precepts of the CP concept mandate, once  $W'$  is expended, would this stable power output be CP?

Our pilot experiments established that the stabilization of power output required approximately 3 min of all-out cycling against a fixed resistance using a Lode Excalibur Sport ergometer (11). Crucial aspects of this test protocol include the following: 1) Subjects need to be highly motivated and fully familiarized with the test protocol before data collection. 2) During the test, pacing is prevented by absence of any time-based feedback, and the subject is strongly encouraged to maximize cadence, and therefore power output, at all times. 3) A valid test is characterized by a  $\dot{V}O_2$  response that depicts no decremental trend at any point during the test and attains >95% of ramp test-determined  $\dot{V}O_{2\max}$ . In our experience, having carried out eight experimental studies in two laboratories using the 3-min test, healthy untrained subjects are capable of reaching  $\dot{V}O_{2\max}$  within the first 60 s and sustaining this for the remainder of the test.

When these conditions are met, a distinct plateau in power output is present within 3 min. The end-test power output, as calculated from the mean power output during the final 30 s of the test, occurs at a power output significantly above the GET but significantly below the power output recorded at the end of a ramp test (i.e., at approximately one-third of peak power; Fig. 6A) (11). One remarkable feature of this response is that  $\dot{V}O_{2\max}$  is not only achieved extremely rapidly but also sustained, confirming that all-out exercise can provide a maximal challenge to the aerobic system (24,84) despite the relatively modest end-test power output.

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Practically, these experiments demonstrated that end-test power in the 3-min all-out test was near CP. This is in agreement with CP theory, in that once the  $W'$  has been used, the highest power output that can be attained is CP because (as defined in equation 1.3)  $P = (W'/t) + CP$ , and therefore, when  $W' = 0$ , this equation reduces to  $P = CP$  (11,70). Moreover, the work performed in the 3-min test above CP (termed “WEP”) should equal  $W'$ . This logic led us to test the hypothesis that the CP and  $W'$  parameters could be established using a single 3-min all-out test. To demonstrate



**FIGURE 6—(A)** Power profile during a 3-min all-out test in a well-trained cyclist. *Dashed lines* represent the power output achieved at the end of a 30 W·min<sup>-1</sup> ramp test (*upper*) and the power output associated with the GET (*lower*). Note the similarity of the end-test power (316 W) with the independently determined critical power (317 W, *dotted line*). **(B)** Correlation between the critical power and the end-test power during the 3-min all-out test from the study of Vanhatalo et al. (70). *Dashed line*, line of identity; *solid line*, best-fit least-squares linear regression. **(C)** Knee extensor torque during 60 intermittent MVC performed in a 5-min period in a single subject (data reproduced from Burnley [9]). *Dashed line* represents the independently determined critical torque. As with the responses to cycle exercise, the “end-test torque” (74.3 N·m) coincides closely with the critical torque (74.2 N·m).



that the CP and the end-test power were synonymous, it was necessary to measure CP independently, in the same subjects, using established methods (i.e., five tests to fatigue performed on separate days). When this was done, the end-test power in the 3-min all-out test closely matched CP (Fig. 6B) (70). Indeed, in 8 of 10 cases, the end-test power was within 5 W of CP. Moreover, the WEP was not different from  $W'$ , although the results were considerably more variable for this parameter (70).

An important feature of the CP concept is that it conflates mechanical (i.e., power) and metabolic ( $\dot{V}O_2$  and lactate) response profiles according to the established behavior characteristic of the heavy- and severe-intensity exercise domains (Historical bases for the critical power concept and Mechanistic bases of the critical power concept sections) (11,64). Thus, when constant-load exercise was performed 15 W below the end-test power, 9 of 11 subjects completed 30 min of exercise and 7 did so, achieving our criteria for the attainment of a steady state (<1 mM increase in blood [lactate] from 10 to 30 min). In contrast, none of the subjects completed 30 min of exercise above the end-test power, with exhaustion occurring within 13 min, on average. During exercise above the end-test power,  $\dot{V}O_2$  rose to reach  $\dot{V}O_{2max}$  at exhaustion, and blood [lactate] continued to increase. These data provide further support that the 3-min end-test power occurs near the heavy/severe-intensity exercise domain boundary (i.e., CP) and also the maximal steady state for  $\dot{V}O_2$  and [lactate].

The correspondence between the parameters of the 3-min all-out test (end-test power and WEP) and those of the  $P-t$  relationship (CP and  $W'$ ) was further investigated using interval training (72) and previous exercise (74). Specifically, 4 wk of high-intensity interval training increased the conventionally established CP and the 3-min test end-test power by ~25 W, with no difference between CP estimates derived from different protocols either before or after training (72). Previous high-intensity or sprint exercise, followed by limited or no recovery time to restore intramuscular  $W'$ -associated energy stores (19,54,58,64), has been shown to reduce the  $W'$  (17,28). Similarly, a 30-s all-out sprint performed 2 min (but not 15 min) before a 3-min all-out test reduced WEP but not the end-test power (74). These investigations have demonstrated that the end-test power and WEP are sensitive to interventions expected to influence CP and/or  $W'$ . Other interventions that have been used to manipulate the 3-min all-out test performance include protocol manipulation (71) and dietary supplementation (75,76). Both the end-test power and the WEP were shown to be unaffected by short-term dietary creatine loading (75), short-term bicarbonate ingestion (76), and pacing during the first 30 s of the all-out test (71).

Collectively, the evidence summarized above supports that 3-min end-test power and WEP represent faithful estimates of CP and  $W'$ , respectively. However, the possibility that the agreement between parameters is coincidental rather than mechanistic must be considered: perhaps because of the arbitrary selection of a fixed resistance on the one hand (71)

and of the limits placed on power output consequent to the attainment of  $\dot{V}O_{2max}$  on the other (11,72). In contrast, if the power profile of all-out cycle exercise has a fundamental physiological basis, then the performance of a completely different exercise mode should produce similar agreement between end-test muscle performance and the exercise mode equivalent to CP. To test this supposition, Burnley (9) investigated the agreement between the “end-test torque” measured during a series of intermittent isometric maximal voluntary contractions (MVC) of the quadriceps and the “critical torque” estimated from five separate tests involving submaximal intermittent contractions of the quadriceps continued until task failure (at ~35%–60% MVC). A 5-min period of maximal contractions (3-s contraction and 2-s rest) was required to achieve a plateau in torque at ~29% MVC, and this plateau corresponded to the critical torque (Fig. 6C). In other words, the results of these experiments were strictly analogous to the cycling experiments detailed above and supported the contention that all-out exercise results in the eventual attainment of CP (or torque) irrespective of the mode of exercise.

## MATHEMATICAL FEATURES OF THE CRITICAL POWER CONCEPT

**The two-parameter CP model.** The CP concept defines a two-component bioenergetic supply-and-demand system, which lends itself ideally to mathematical modeling. Both supply components are endogenous, but demand is determined exogenously. As originally defined, the assumptions can be formulated as follows:

- 1) There is an “aerobic” energy supply component that is rate- but not capacity-limited. This rate limit is denoted as the CP.
- 2) There is an “anaerobic” energy supply component that is capacity- but not rate-limited. This capacity limit is denoted as  $W'$ .
- 3) Exercise can continue at any power output as long as supply is adequate to meet demand.

Thus, we can deduce that if an individual exercises continuously at a constant power  $P$  less than or equal to CP, exercise duration is “infinite” because the entire demand can be met aerobically, and the limit of tolerance cannot be predicted using the power–duration relationship. On the other hand, if  $P > CP$ , then the aerobic supply alone is insufficient, and the excess power requirement above CP must be met by using the  $W'$  component. The length of time until exhaustion,  $t$ , that this excess requirement can be sustained can be deduced by dividing the available capacity,  $W'$ , by the rate at which it is required ( $P - CP$ ), yielding:

$$t = W' / (P - CP) \quad [4.1a]$$

Because this equation defines a rectangular hyperbola, asymptotic to the horizontal axis at  $t = 0$  and to the vertical axis at

$P = CP$ , it is usually called the hyperbolic form of the CP model. Because the total amount of work,  $W$ , accomplished during the interval 0 to  $t$ , is given by  $W = Pt$  (Fig. 1), five other algebraically equivalent equations can be deduced:

$$P = W'/t + CP \quad [4.1b]$$

$$W = W' + CPt \quad [4.1c]$$

$$t = (W - W')/CP \quad [4.1d]$$

$$W = W'P/(P - CP) \quad [4.1e]$$

$$P = CPW/(W - W') \quad [4.1f]$$

Equations 4.1c and 4.1d are linear forms, the former well known and due originally to Monod and Scherrer (54). All the other equations are hyperbolae, although equation 4.1b is usually linearized by substituting  $x = 1/t$ . It is important to realize that, although mathematically equivalent, these equations are not statistically equivalent when it comes to estimating the parameters from collected data (21,34). Equation 4.1a with  $t$  as dependent variable and  $P$  as independent is the most natural to use, although equations 4.1c and 4.1d are almost as natural, and 4.1b using  $x = 1/t$  is often used. Given the capabilities of modern computing equipment, there is no reason to prefer a linear to a hyperbolic equation. Application of the model is unlimited by exercise modality as long as any two of the three variables  $t$ ,  $P$ , or  $W$  (or their analogs, velocity and distance, in other exercise modalities) can be measured.

The two-parameter CP model has been adapted for ramp exercise (56), where the ramp rate (or slope) variable,  $s$ , is used in place of  $P$ . In this instance, assuming that  $P = 0$  at  $t = 0$ , whence  $W = 1/2st^2$ , there are similarly six algebraically equivalent equations. As  $s$  is the only logical independent variable, the most natural and mathematically simplest equation is as follows:

$$t = CP/s + \sqrt{(2W'/s)} \quad [4.2a]$$

although

$$W = W' + CP^2/s + \sqrt{(2W'CP^2/s)} \quad [4.2e]$$

could be used if work is to be measured as the dependent variable. Early evidence (61) suggests that parameter estimates obtained for the same subjects from ramp and constant-power protocols are equivalent.

The two-parameter CP model has also been adopted for intermittent exercise (60). In this application,  $n$  is the number of completed work and rest cycles;  $t_w$  and  $t_r$  are the durations, and  $P_w$  and  $P_r$  are the power outputs of the corresponding work and rest periods, respectively.  $n$  is observed as exercise proceeds, but  $t_w$ ,  $t_r$ ,  $P_w$ , and  $P_r$  are set before exercise commences. Subject to certain constraints on

feasible combinations of these last four variables, total endurance time is given by the following equation:

$$t = n(t_w + t_r) + [W' - n\{(P_w - CP)t_w - (CP - P_r)t_r\}]/(P_w - CP) \quad [4.3a]$$

No other equivalent forms of this equation have been published, although they could theoretically be derived. Instead of equation 4.3a, equation 4.1c has been used (4,45) to estimate CP and  $W'$  by cumulating both  $W$  and  $t$  over all the repeated work and rest cycles, whether complete or not. Although unpublished, this can be shown algebraically and numerically to provide the same estimates of CP and  $W'$  as equation 4.3a, and experimental observations have confirmed their equivalence (8).

The three assumptions above are sufficient to derive all the mathematical equations presented so far, but it is important to realize that, in theory, implicitly embedded in these assumptions are several others, specifically:

- 4) Aerobic power is available at its limiting rate CP the moment exercise begins, remaining so until exercise ceases at exhaustion.
- 5) The power domain over which the model applies is all of  $CP < P < \infty$ .
- 6) The time domain over which the model applies is all of  $0 < t < \infty$ .
- 7) CP and  $W'$  are constants, independent of  $P$  and/or  $t$ .
- 8) The efficiency of transformation of metabolic energy to mechanical energy is constant across the whole power (and time) domain(s).

All of these assumptions have been questioned previously (58), and it should be noted that when prediction trials are limited to the severe-intensity exercise domain, where  $2 \text{ min} < t < 15 \text{ min}$  (Historical bases for the critical power concept section) (64), data conform well to the original two-parameter model. The fine-tuning of the mathematical model, as discussed below, may allow the extension of this applicable range at the extremes of the power (and time) continuum or improved fit when using different exercise modalities.

To deal with assumption 4), Wilkie (83) introduced a correction factor for oxygen uptake kinetics on the basis of a single exponential with time constant  $\tau$  and without delay. Replacing the  $E$  designating power at  $\dot{V}O_{2\text{max}}$  in Wilkie's original suggestion with CP (equation 1.1), equation 4.1c now becomes:

$$W = W' + CPt - CP\tau(1 - e^{-t/\tau}) \quad [4.1g]$$

If  $\tau$  is known and times to exhaustion no less than about  $3\tau$  are used in the estimation of  $W'$  and CP, then the exponential term may be regarded as negligible, and a revised and larger estimate of  $W'$  can be obtained by adding  $CP\tau$  to the original  $W'$  estimate. However, if  $\tau$  is unknown, it may be estimable using equation 4.1g if sufficient short-duration (i.e.,  $t < 3\tau$ ) trial data are collected. No correction factor has been published or derived for any of the other forms of equations 4.1,

4.2, or 4.3, although the unnecessarily complex mathematics could be done if required.

**The three-parameter CP model.** The three-parameter CP model (57) has been developed to deal with assumptions 5), 6), and 7) simultaneously, although assumptions 4) and 8) remain in force. The key difference between the two- and three-parameter models from a mathematical standpoint is simply that the horizontal asymptote of the rectangular hyperbola (where  $P$  is plotted as the independent and  $t$  is plotted as the dependent variable) is no longer constrained to  $t = 0$  but rather regarded as a real third parameter that can be estimated from the data at  $t = k$ , where  $k$  is the temporal asymptote. Equation 4.1a is therefore reformulated with the third parameter as:

$$t = W'/(P - CP) - k \quad [4.4a]$$

From a physiological standpoint, the three-parameter model conjectures a dynamic feedback that limits maximal available power output between a finite amount ( $P_{\max}$ ) and CP, according to the existing anaerobic energy supply at any instant, where  $P_{\max}$  can be interpreted as a maximum “instantaneous power.” Graphically, it is because  $k < 0$ ,  $P_{\max}$  is the finite point where the hyperbola crosses the horizontal axis at  $t = 0$ . In practical terms what this means is that when a subject is fully rested,  $P_{\max}$  could be developed as a maximal effort, but when the anaerobic store is fully depleted, only CP could be developed. Between these extremes, maximal power declines proportionally. This manifests, for example, by observing that a maximal finishing sprint at the end of, say, a 1500-m race is not as fast it would be if the athlete was fully rested.

As previously, there are six algebraically equivalent equations. Equation 4.4a is the most natural, but:

$$W = W't/(t + k) + CPt \quad [4.4c]$$

or

$$t = [W + CPk - W' + \sqrt{\{(W + CPk - W')^2 - 4CPkW\}}]/2CP \quad [4.4d]$$

could both be contemplated. The temporal asymptote  $k < 0$  is unhelpful from a physiological standpoint because negative endurance times are meaningless. More relevant physiologically is  $P_{\max}$ , so  $k$  can be replaced if preferred by the reparameterization  $W'/(P_{\max} - CP)$ . Equation 4.4c is an upward-sloping concave curved line, starting at 0 and tending toward the straight line (equation 4.1c) from below for large  $t$ . Indeed, data “dropping below” the straight line in this way (see Bishop et al. [6], their Fig. 2, p.127) (54) are frequently observed phenomena when  $t$  durations span a wider range. Note that letting  $k = 0$  in any of equations 4.4 reduces them to the corresponding versions of equations 4.1. If  $k$  is reparameterized, letting  $P_{\max} \rightarrow \infty$  achieves the same result. Note also that like the two-parameter model, the three-parameter model is unlimited by exercise modality, as long as any two of the three variables  $t$ ,  $P$ , or  $W$  (or their analogs, velocity and distance, in other forms of exercise) can be measured.

There are no published equations or applications, as yet, of the three-parameter model to ramp exercise. The mathematics can easily be done, yielding as the most natural equation:

$$t = CP/s + k + \sqrt{(k^2 + 2W'/s)} \quad [4.5a]$$

and it will be again noted that, when  $k = 0$  (or letting  $P_{\max} \rightarrow \infty$  in the reparameterization), this equation reverts to the two-parameter equation 4.2a. Further mathematically equivalent equations could be algebraically derived if desired. No three-parameter equations for intermittent exercise have yet been developed, although it may be speculated that using the cumulative procedure described above ought to work with equation 4.4c.

The feedback system of the three-parameter model permits the investigation of another exercise modality, all-out effort, not possible with the two-parameter model where  $P$  is unbounded. Morton (59) has shown that the time course of power output during all-out effort declines exponentially from  $P_{\max}$  at  $t = 0$ , asymptotically to CP as  $t \rightarrow \infty$  according to the following equation:

$$P = CP + (P_{\max} - CP)e^{-t/k} \quad [4.6b]$$

In practice, there is usually a short-lived period of buildup of  $P$  observed, due, for example, to inertial or acceleration considerations (11,59), rather than observing a genuine  $P_{\max}$  start at  $t = 0$  (Fig. 6A). By integrating equation 4.6b assuming a zero start, work performed,  $W$ , follows an exponential rise toward linearity with time according to the equation:

$$W = W'(1 - e^{-t/k}) + CPt \quad [4.6e]$$

In some applications,  $W$  (or more usually, its analog distance) may be given, and  $t$  is the dependent variable. Reversing the variables in equation 4.6e is not possible because equation 4.6e is a transcendental equation in  $t$ , and an iterative solution to equation 4.6e is the only feasible expedient. In respect to assumption 4), Wilkie’s correction applied to the three-parameter model has not been published for any of the three-parameter equations given, although again the mathematics could be done if required.

**Mathematically optimal strategies.** Given the relevance in today’s world of competitive sports performance, and the reward accruing to winners, it is natural to ask whether performance time (or the amount of work accomplished) can be mathematically optimized. The early work of Keller (46) gives a hint of the complexities. Nevertheless, Fukuba and Whipp (19) have investigated the problem for the two-parameter CP model. They demonstrate that there is no unique optimal strategy, in that any one of an infinite number of strategies, involving stagewise steps of periods of constant power, produces an identical endurance time, provided that  $P$  never drops below CP. In fact, any smooth and continuous trace of  $P$ , never dropping below CP, will also yield exactly the same endurance time because the integral of  $P$  above CP equals  $W'$ . That this is so is a direct

consequence of the lack of any feedback system in the two-parameter model.

The situation in the three-parameter model is quite different. It has been mathematically proven that there is a unique optimal solution, although it may be as unacceptable to as many sport scientists as is the above solution for the two-parameter model, albeit for different reasons. That unique strategy turns out to be maximal all-out effort for the entire duration of the exercise (59), and equations 4.6b and 4.6e apply. As an optimal strategy, all-out effort for a short-duration exercise is universally accepted, but for a longer-duration exercise, it quite definitely runs counterintuitively to what is generally believed and what is normally practiced. Nevertheless, it fits well to at least 3 min of all-out data (59), and it can quite easily be numerically demonstrated to be optimal. Despite some empirical evidence of the superiority of faster starting (e.g., Jones et al. [43]), this raises a question mark concerning the three-parameter model.

## PRACTICAL APPLICATIONS OF THE CRITICAL POWER CONCEPT

The CP and  $W'$  parameters that can be deduced from the  $P-t$  relationship for severe-intensity exercise domain have a variety of applications in sport and exercise science and medicine, although these have not been as widely appreciated to date as, perhaps, they should be. These applications include the assessment of physical fitness, the prescription of exercise training, and the prediction of performance during high-intensity exercise. Although this section will focus on competitive athletes, it should be noted that many of these same concepts could be equally applied to other populations including patients, physical laborers, and those involved in recreational physical activities. However, in athletes, an understanding of the CP concept is additionally important in the design of optimal warm-up programs and in informing pacing strategy and the tactics used during a competition.

As has been highlighted earlier in this review, there is evidence that the CP represents the highest power output that can be sustained without a progressive loss of homeostasis as indicated by 1) a continuous decline in muscle [PCr] and pH and in blood pH and [bicarbonate] and 2) a continuous increase in blood [lactate], pulmonary  $\dot{V}O_2$ , and ventilation (42,64). These data, along with evidence that the CP occurs at a similar exercise intensity to the so-called “maximal (lactate) steady state” (66), have led to the suggestion that the CP represents the highest rate of oxidative metabolism that can be sustained without a progressively increasing contribution to energy turnover from substrate-level phosphorylation (i.e., PCr hydrolysis and “anaerobic” glycolysis). In contrast, the  $W'$  represents a fixed amount of work (kJ) that can be completed during exercise above the CP, which is derived principally from anaerobic processes. Although it is becoming clear that  $W'$  is a mechanical work capacity that is related, at least in part, to the “distance”

between the CP and the  $\dot{V}O_{2\max}$  rather than to an “anaerobic capacity,” *per se*, it is notable that the CP increases because of continuous or interval endurance training (23,38,65,72) and that the  $W'$  increases because of power or sprint training (39), although the effects are not mutually exclusive. The measurement of changes in the  $P-t$  relationship after a training intervention is likely to be functionally more valuable than the measurements of discrete physiological constructs such as, for example,  $\dot{V}O_{2\max}$ , GET/LT, or “anaerobic power.” However, the requirement for subjects to complete a series of constant work rates to exhaustion both before and after the training period has possibly precluded widespread assessment of training-induced changes in the  $P-t$  relationship in practice. In this regard, the advent of a single all-out test for the estimation of CP and  $W'$  (Application of the critical power concept to all-out exercise section) (11,70), which is sensitive at least to endurance training (72), might facilitate more routine assessment of changes in the  $P-t$  relationship after training.

Given that the time-to-exhaustion ( $t$ ) at a specific constant severe-intensity power output can be accurately estimated using equation 4.1a, it is clear that knowledge of an individual athlete's CP and  $W'$  parameters should enable exercise performance capacity (i.e., the time required to cover a given distance) to be accurately predicted. For example, if a distance runner wishes to complete a continuous severe-intensity training run (often termed “tempo” running), then the maximum sustainable time for a given velocity will be given by:

$$t = D/(V - CV) \quad [5.1]$$

Also, the shortest time that the runner could complete a given distance ( $D$ ) is given by:

$$t = (D - D')/CV \quad [5.2]$$

If the runner's CV is  $6.0 \text{ m}\cdot\text{s}^{-1}$  and his/her  $D'$  is 150 m, then the endurance time at a velocity of  $6.2 \text{ m}\cdot\text{s}^{-1}$  would be 750 s (12.5 min), and the endurance time at a velocity of  $6.1 \text{ m}\cdot\text{s}^{-1}$  would be 1500 s (25 min). This information could be used by a coach to prescribe a training session that is challenging but manageable, resulting in physiological adaptation but with the avoidance of overreaching. The CP concept can also be applied in the design of interval training sessions (60). With the assumption that the power output during the work interval ( $P_w$ ) is greater than CP (but not so great that exhaustion occurs within the first bout of work) and that the power output during the recovery interval ( $P_r$ ) is less than the CP, it can be calculated that the  $W'$  during exercise will be consumed by a function of:

$$(P_w - CP)t_w \quad [5.3]$$

and that the  $W'$  during recovery will be restored as a function of:

$$(CP - P_r)t_r \quad [5.4]$$

If the mean power output over the work/recovery cycle is greater than the CP, then  $W'$  will fall predictably at the end



of each work interval, and the endurance time for any combination of work interval power output, recovery interval power output, work interval duration, and recovery interval duration (i.e., the number of complete work intervals and one partial work interval that can be accomplished before  $W'$  is expended) can be calculated (equation 4.3a). This assumes that the CP and  $W'$  are essentially the same during intermittent exercise as during continuous exercise and that the processes that consume and restore  $W'$  are linear, assumptions that are yet to be verified (60).

Knowledge of CP and  $W'$  will also enable an athlete and his or her coach to make informed decisions on appropriate pacing and tactical strategies to maximize competitive performance. One important consideration, which is often overlooked, is that the time to cover a given competitive distance depends not only on the metabolic capability of the athlete but also on the athlete covering the minimum possible distance for the event. For example, if we consider the 5000-m track event, an athlete will only cover 5000 m if he or she runs close to the curb for the entire distance, something that is rare in practice. If the athlete runs wide on the bends, the actual distance covered can be significantly increased. Taking an extreme example, an athlete who ran in the second lane for the entire 5000-m event would actually cover approximately 5100 m (equivalent to giving a more conservative opponent a head start of 100 m).

It can be shown that an athlete's maximal mean velocity for a given distance (and hence, the shortest time possible for that distance) is dictated by the crossing point of his or her individual velocity-time curve and the distance-time curve (Fig. 7). Where the athlete covers a distance that is greater than the theoretical race distance, the point of inter-

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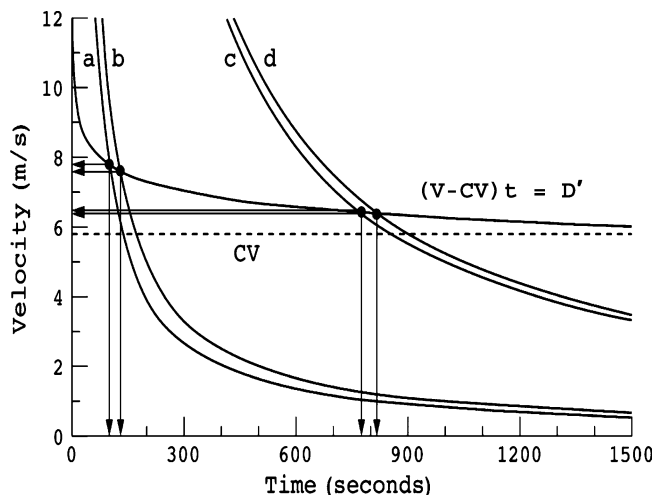


FIGURE 7—Schematic illustration of the effect of race distance on the time to complete the race. Curves *a* and *c* are the distance curves to 800 and 5000 m, respectively; curves *b* and *d* are examples of distance curves that may pertain if the athlete did not run the shortest possible distance (e.g., by running wide on the bends in track races). Note that because of the shape of the individual  $V-t$  curve, a small reduction in average velocity results in a relatively large increase in race time as race distance increases. See text for detailed explanation. Redrawn from Jones and Whipp (40).

section will move downward and to the right, thus reducing the maximal mean velocity and increasing the time taken to complete the distance (Fig. 7). These considerations are not just theoretical. Jones and Whipp (40) have reported that the athletes who ran at the highest mean velocity in both the 800- and 5000-m events at the Olympic Games in 2000 were not the winners of those races; rather, the winners were able to husband their metabolic resources to better effect by running closer to the actual race distance. Thus, athletes in these and other events and sports that are performed in the severe-intensity exercise domain should be conscious of minimizing the distance covered in any competition because the race outcome is not simply a function of the energetic potential of the athlete at the outset of the competition.

Knowledge of the ratio  $D'/CV$  (or  $W'/CP$ ) might also prove useful to the athlete and coach in terms of the selection of competition tactics that play to the metabolic strengths of the athlete and/or act to expunge the metabolic advantages of a competitor. Fukuba and Whipp (19) have demonstrated mathematically that for severe-intensity exercise (which spans the 800-, 1500-, 3000-m steeplechase and 5000- and possibly 10,000-m races in track athletics), the theoretical best time for a given distance can never be attained if any portion of the race distance is covered at a velocity below CV (i.e., it is not possible to “make up for lost time” with a sprint finish). Moreover, the “endurance parameter ratio” ( $D'/CV$ ) dictates the flexibility of the race pace that can be selected while still enabling an athlete to attain their best mean velocity for the distance. Therefore, the best tactics for an athlete with a high CV and a low  $D'$  relative to the rivals might be to operate at the highest possible mean velocity for the distance (as dictated by their individual velocity-time relationship). In contrast, an athlete with the opposite metabolic characteristics would do better to attempt to slow the race pace down below their main rival's CV for some portion of the race and to use their superior  $D'$  in a sprint finish.

It is, of course, possible that the performance impact of the  $D'/CV$  ratio is intuitively known by athletes and that this “subconsciously” dictates their pacing strategy. However, information on the  $D'$ , CV, and  $D'/CV$  ratio might still prove invaluable in precompetition comparison of the metabolic “strengths” and “weaknesses” of individual athletes and the creation of tactical plans designed to optimize performance. With regard to the latter, there is increasing evidence that a fast start (43) or even an all-out pacing strategy (59) might optimize performance at least during exercise at the upper end of the extreme domain (i.e., 2–3 min in duration). A fast-start strategy results in a faster rise of  $\dot{V}O_2$  toward the maximum, thus resulting in a greater overall  $O_2$  consumption during the exercise bout (10,43). Given the same energy yield through the complete depletion of  $W'$ , this would be expected to enhance exercise tolerance or performance. The completion of a “priming” bout of exercise has the potential to enhance performance during subsequent high-intensity exercise at least in part through a similar mechanism (10,17,41). Further research is required to

ascertain the effects of different pacing strategies and previous exercise protocols on the CP and  $W'$  and their relationships to changes in  $\dot{V}O_2$  kinetics.

The relative importance of the CV and  $D'$  to success in different events can be illustrated about two hypothetical elite female endurance athletes and the use of equation 5.2. Assume that athlete A has a CV of  $5.85 \text{ m}\cdot\text{s}^{-1}$  and a  $D'$  of 75 m, whereas athlete B has a marginally inferior CV of  $5.82 \text{ m}\cdot\text{s}^{-1}$  but a superior  $D'$  of 95 m. In a head-to-head race of 800 or 1500 m, it can be calculated that athlete B would be the clear winner (by around 3 and 2 s, respectively). However, at 3000 m, the predicted difference between the athletes becomes negligible, and at 5000 m and beyond, it can be calculated that athlete A would have an increasingly significant advantage. Theoretically, this concept could be used by handicappers in selecting the race distance at which the metabolic capabilities of two athletes (e.g., a 1500-m specialist and a 5000-m specialist) are precisely matched, thus guaranteeing the closest of finishes for the benefit of spectators!

This section has provided some of the practical applications of the CP concept to human athletic endeavor. However, it is reiterated that the concept also has important implications for understanding exercise intolerance, describing exercise performance potential, and investigating the efficacy of potentially ergogenic interventions in diseased as well as healthy populations (62) and in the elderly as well as the young (63). Indeed, in almost all situations, it might be considered that the CP (and  $W'$ ) is more relevant, from a functional perspective, than are the more commonly measured aerobic performance parameters of LT/GET and  $\dot{V}O_{2\text{max}}$ . Along with others (79), we therefore urge that, wherever possible, this is taken into account in the design

of studies that are interested in defining or enhancing exercise tolerance.

## CONCLUSIONS

The hyperbolic two-parameter (i.e., CP,  $W'$ ) power-time ( $P-t$ ) relation defines exercise tolerance within the severe-intensity exercise domain for  $t$  (time-to-exhaustion) values between approximately 2 and 15 min. Thus, all metabolic rates above CP (or CV, the asymptote for power or velocity) yield an inexorable increase in both  $\dot{V}O_2$  (to  $\dot{V}O_{2\text{max}}$ ) and blood [lactate], as  $W'$  is progressively depleted to fatigue. Whereas the time-to-exhaustion can be manipulated by altering work rate and/or  $O_2$  supply, for example, the within-subject fatigue process is characterized by depletion of  $W'$  and corresponding perturbations of intramuscular [PCr] (close to 100% depletion),  $[P_i]$  and  $[H^+]$ . In marked contrast, work rates at or below CP (i.e., in the heavy domain) facilitate achievement of an apparent steady state for  $\dot{V}O_2$  and blood [lactate] as well as for intramuscular [PCr],  $[P_i]$ , and  $[H^+]$ . Knowledge of an athlete's CP (or CV) and  $W'$  (or  $D'$ ) can be used to refine and monitor training protocols and to optimize competition pacing strategies. Hopefully, the recent development of a single test to define an individual's CP and  $W'$ , combined with the development of  $P-t$  models that encompass exercise durations outside the 2- to 15-min window and intermittent exercise, will help the CP concept fulfill its considerable potential utility in exercise science and medicine.

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