Applying the Critical Speed Concept to Racing Strategy and Interval Training Prescription

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The use of personal records (PRs) for running different distances may be used to derive critical speed (CS) and the finite capacity for running speeds exceeding CS (D'). Using CS and D', individualized speed-time and distance-time relationships can be modeled (ie, time limits associated with running at a given speed or a given distance can be derived via linear regression with a high degree of accuracy). The running 3-min all-out exercise test (3 MT) has emerged as a method for estimating CS and D' on a large group of athletes in a single visit. Such a procedure is useful when PRs are not readily available (eg, team-sport athletes). This article reviews how to administer and interpret the running 3 MT, how CS and D' can inform racing strategy, and how CS and D' can be used to prescribe and evaluate high-intensity interval training (HIIT). Directions for deriving HIIT bouts using either fixed distances or fixed speeds are provided along with CS dose-responses to short-term HIIT programs.

Keywords: 3-minute all-out exercise test, anaerobic power, critical power, high-intensity, severe domain

The severe exercise domain is characterized by an intensity too severe to permit a steady state of oxygen uptake (VO₂), resulting in the reliance of anaerobic energy pathways. The basis for prescribing HIIT in the severe exercise domain begins by determining an athlete's CS. Critical speed is a mechanical measure that has been suggested to represent the maximal lactate or VO₂ steady state. Metabolic steady states of VO₂ are unattainable >CS and may evoke values approaching and achieving maximum VO₂ (VO₂max). The pronounced time-dependent rise in VO₂ toward VO₂max during constant-speed running is termed the VO₂ slow component, an event largely attributed to the recruitment of type II muscle fibers. Indeed, by engaging in HIIT in the severe domain, improvements in CS and overall running performance can be achieved, resulting in attenuation of the VO₂ slow component and less reliance of type II muscle fibers.

This review describes procedures for modeling the speed-time and distance-time relationships from prior personal record (PR) running performances or running 3 MT. Procedural considerations of the running 3 MT are also discussed. The modeling of performance data from 2 former Olympic runners is used to explain the utility of the CS concept for developing racing strategy. Finally, a simple application of the CS concept on prescribing and assessing HIIT is summarized.

Modeling Maximal Performance Capacity

The CS concept originated as a method of modeling the total work capacity of an isolated exercising muscular group relative to the time of force decline. The method was adapted subsequently for leg cycle ergometry and slightly later for running. In running, it is common to derive CS and the finite capacity for running speeds exceeding CS (D') from PR times of different distances, although exhaustive times for runs of different supramaximal running speeds on a treadmill have been used. Take for example, Steve Prefontaine (referred to as “Pre” in this review), a middle-distance runner who during the late 1960s and early 1970s, held every US distance running record between 2000 m and 10,000 m. Plotting Pre’s PR times over various race distances indicates his CS was 6.0 m/s and his D' was 200 m (Figure 1A). Figure 1A reflects Pre’s PRs associated with 4 running distances (D). Using linear regression, the distance associated with a given time limit (t_LIM) may be resolved using

D = (CS × t_LIM) + D'  \hspace{1cm} (Eq 1)\

where D and D' are in meters, CS is in meters per second, and t_LIM is in seconds. The t_LIM for a given distance may be resolved using

D = (D' − D'_{0})/CS  \hspace{1cm} (Eq 2)\

A desired running speed (S) for a given t_LIM may be resolved using

S = D'/t_LIM + CS  \hspace{1cm} (Eq 3)\

Modeling high-intensity performance for an individual athlete also may be projected from a single 3 MT. The 3 MT is particularly useful for team sport athletes, where PR times of different distances are not readily known. Moreover, the modeled t_LIM values can be used to prescribe and monitor responses to HIIT. The utility of the 3 MT is that the parameters of CS and D' may be derived on a group of athletes in a short period of time.
Summary of the Running 3 MT

The 3 MT emerged as a method of deriving estimates of CP and the work capacity exceeding critical power (\(W\)) in cycle ergometry.\(^{13,14}\) The 3 MT procedures developed subsequently for running entail having the subject build up their running speed to avoid muscle strain (eg, hamstrings) until reaching their maximal speed.\(^{12}\) Once maximal speed is achieved, the athlete attempts to sustain that speed for as long as they can and is instructed to run all-out until told to stop, typically at a time of 3:05 to ensure a full sampling of 3 minutes of data. Our subjects are counseled to expect that about halfway through the 3 MT, they will experience a sense of demoralization. Despite the urge to quit, subjects are encouraged to keep going. The objective of the test is to wholly deplete and measure work capacity exceeding critical power (\(W\)) in cycle ergometry.\(^{13,14}\) Conversely, fixed loads for cycle ergometry are derived using a linear factor from a preliminary incremental exercise test\(^{13,14}\) or a fixed percentage of body mass.\(^{16-18}\) For such 3 MTs, the load is "inescapable," similar to the Wingate anaerobic power test,\(^{19}\) whereby the subject pedals against a fixed load for a fixed amount of time. With the running 3 MT, athletes have the option to hold back and pace to ensure a stronger finish, although they are instructed not to do so. As the CS is estimated using the end speed of the test, if an athlete paces and a sudden end-spurt in speed ensues, that athlete will not truly expend all of \(D'\) during the initial 150 seconds, resulting in an inflated estimate of CS and a low estimate of \(D'\). Having evaluated the running 3 MT on more than 400 subjects, I have tested and retested numerous subjects suspected of excessive pacing. Of those retested, the paced test is characterized by a nadir of speed at their true CS between ~120 and 160 seconds, with the end spurt occurring between 160 and 180 seconds. When such a speed-time profile is observed, retesting when possible is recommended. For research purposes, the CS estimate from the 3 MT may be compared with the average value from the speed-evoking gas exchange threshold (GET) and \(\text{VO}_2\max (50\% \Delta)\) during an incremental exercise test.\(^{12}\) Others have examined \(\text{VO}_2\) responses at constant speed bouts less than and greater than the CS estimate; whereby, the bout less than CS should evoke \(\text{VO}_2\) steady state and the bout greater than CS should evoke \(\text{VO}_2\max\) and culminate in fatigue (ie, exercise in the severe domain).\(^{11}\) Alternatively, seeing the athletes perform their interval training bouts also can help in determining whether an athlete has paced. If an athlete has an inflated CS estimate, she or he will find it impossible to make the prescribed times for many of their intervals and, in particular, longer intervals. Conversely, if the 3 MT results are accurate, which they typically have been in my experience, the interval prescriptions will be very challenging but achievable.

All-Out and Race Performances Conform to the Kinetic Energy Equation

The fastest running speeds for running different distances has been characterized as a "hyperbolic relationship."\(^{3}\) Simply stated, the faster one's running speed, the quicker the time to exhaustion, and an individual's performance from the 3 MT can be modeled to construct both velocity-time and distance-time relationships (Figure 2). Interestingly, when first modeling the \(f_{\text{LIMs}}\) associated with different distances, I used the default unit of measurement for treadmills and GPS sensors in the United States (miles per hour [mph]). Although the unit of measurement of mph-150 s is nebulous, when algebraically transformed, the calculation of \(f_{\text{LIMs}}\) was still
example, the total projected distance he would have covered was proportional energetic information, which may provide an understanding of training status. Using Pre’s $S_{150}$ performance as an example, the total projected distance he would have covered was 1100 m (ie, 7.33 m/s x 150 s) (note: this same datum point is illustrated in Figure 1A). The fractional contribution of his $D'$ would have been ~18% (ie, his $D'$ divided by the total distance covered or 200 m/1100 m). As distances are extended, the contribution of $D'$ to total distance declines exponentially. Conversely, the contribution of CS to total performance increases exponentially, as illustrated with the 900 m distance bins in Figure 2B. From the all-out test, it is evident that Pre had a high CS, with 82% of his energy for his $S_{150}$ performance coming from his superior aerobic system. Indeed, a CS of 6 m/s is shared by gold-medal distance running winners within the past century.20 As the CS concept is evaluated in more sports, we will gain a better idea of normative CS and $D'$ data and proportions that are optimal for different athletes and sports.

How the Critical Speed Concept May Inform Racing Strategy

When investigating the running 3 MT, 2 runners we observed had identical GET and VO$_2$-max values.12 Using the metric of running economy (ie, the percentage of GET relative to VO$_2$-max),21 these runners may have been deemed “identical.” Yet 1 runner had a higher CS and a lower $D'$ compared with the other (note: the athlete with the higher $D'$ also had a higher speed evoking VO$_2$-max). In their 3 MTs, the runner with the superior $D'$ would cover more distance in the beginning of the test; however, the “identical” runner with the superior CS would ultimately run a longer total distance over the span of 180 seconds. Such performance differences would indicate that each runner should use different racing strategies.

To explain racing strategy, the example of Pre using the 5000-m event of the 1972 Olympic Games in Munich is useful. Leading up to the event, an epic race was anticipated by the up-and-coming college runner Pre and the favored runner from Finland, Lasse Virén. As indicated, Pre had a CS of 6 m/s and a $D'$ of 200 m (Figure 1). Using the same procedure that formed Figure 1, Virén was modeled to have had a CS of 5.87 m/s and a $D'$ of 267 m. The notable disparities between these runners are as follows: Pre had a superior CS (+0.12 m/s) whereas Virén has a superior $D'$ (+67 m). In layperson’s terms, Virén had a “kick” that was feared by his competitors. Indeed, his $D'$ at that time exceeded 4 SDs above the mean $D'$ of Gold Medal winning Olympic distance runners during that century.20

With a $D'$ of 200 m, Pre could have sustained a running speed +0.25 m/s relative to his CS of 6 m/s for 5000 m (see Figure 2[A]). At a velocity of 6.25 m/s, covering a distance of 5000 m, Pre’s time would have been 13:20. That performance would have eclipsed the Gold winning performance by Lasse Virén of 13:23.4. With knowledge from the 3 MT, physiologists today would have told Pre that he was best advised to adopt a front running strategy rather than holding back. A front running strategy involves running faster split-times within a given race rather than trying to “store energy” for his VO$_2$-max. In their 3 MTs, the runner with the superior $D'$ would cover more distance in the beginning of the test; however, the “identical” runner with the superior CS would ultimately run a longer total distance over the span of 180 seconds. Such performance differences would indicate that each runner should use different racing strategies.

![Figure 2](image-url)

**Figure 2** — The modeling of individual speed-time and distance-time performances using Steve Prefontaine’s (Pre) data. (A) Six separate data points of the curve, which can be drawn using Equation 2. The horizontal dashed line denotes critical speed (CS). Note that the geometric areas within the rectangles and square are equal, with the top right corner of each shape touching the data points for 150, 300, and 450 seconds. As speed relative to CS is reduced proportionately, time is increased proportionately, as indicated by the x2, x3, and x4 labels. The arrow intersects with an expected time of 800 seconds for “Pre” to run a distance of 5000 m. (B) The proportionality of the distance-time relationship. The 900-m bins represent the running distance supported by CS. The 200-m bin represents the $D'$. Take notice that as the total distance is divided by time, the speeds revealed are equivalent to the data points adjacent to the $\downarrow 1/2$ and $\downarrow 1/3$ labels.

The units of measurements were indeed arbitrary because the relationship between running speed and $f_{LIM}$ is proportionate and conforms to the kinetic energy equation.2

The kinetic energy equation is a useful construct for appreciating the true proportionality of CS and $D'$ to total performance. To demonstrate conformity of the CS concept to the kinetic energy equation, consider the following example. If we project the $f_{LIM}$ for Pre running at one-half of the difference between $S_{150}$ and CS, we would arrive at a speed of 6.67 m/s. The resulting $f_{LIM}$ at that speed would double from 150 to 300 seconds (ie, one-half the difference equals double the $f_{LIM}$). A speed of 6.67 m/s would cover an approximate distance of 2000 m, which is the product of 6.67 m/s and 300 seconds. By doubling the time from 150 to 300 seconds, we derive that the energy from the CS metric supported 1800 m (ie, 6.0 m/s x 300 s) and $D'$ supported 200 m (Figure 2B). Equations 1 through 3 corroborate these same distances and speeds.

Using the same math described previously, the 3 MT provides proportional energetic information, which may provide an understanding of training status. Using Pre’s $S_{150}$ performance as an example, the total projected distance he would have covered was 1100 m (ie, 7.33 m/s x 150 s) (note: this same datum point is illustrated in Figure 1A). The fractional contribution of his $D'$ would have been ~18% (ie, his $D'$ divided by the total distance covered or 200 m/1100 m). As distances are extended, the contribution of $D'$ to total distance declines exponentially. Conversely, the contribution of CS to total performance increases exponentially, as illustrated with the 900 m distance bins in Figure 2B. From the all-out test, it is evident that Pre had a high CS, with 82% of his energy for his $S_{150}$ performance coming from his superior aerobic system. Indeed, a CS of 6 m/s is shared by gold-medal distance running winners within the past century.20 As the CS concept is evaluated in more sports, we will gain a better idea of normative CS and $D'$ data and proportions that are optimal for different athletes and sports.

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An athlete with higher $D'$ values can (and should) run at faster speeds relative to their CS because their superior $D'$ enables them to do so. If their peer has a superior CS, the actual speed for that HIIT bout might be actually faster, but their interval speeds would be in closer proximity to their CS. Moreover, with standardized rest intervals, multiple bouts of these HIIT can be performed within a team practice setting (discussed later).

The prescription of HIIT using the CS concept relies upon the relationship between CS, $D'$, and the VO$_2$ slow component. Specifically, at higher speeds relative to CS for any given athlete, $D'$ expenditure will be more rapid along the gain in VO$_2$ toward VO$_2$max (ie, a more rapid VO$_2$ slow component). Figure 3 depicts 2 methods for utilizing the CS concept for HIIT prescription. Figure 3(A) depicts a prescription where 60% of $D'$ is expended over a period of 300 seconds. Figure 3(B) depicts a prescription where the same 60% of $D'$ is expended in the shortened period of 180 seconds (ie, 60% of 300 s, in accordance with the kinetic energy equation). Thus, as the proportional depletion of $D'$ between the 2 HIIT bouts is identical (ie, the geometric area of the rectangles in Figure 3 are the same), the same metabolic response will be observed. Specifically, the rate of rise in VO$_2$ will be more rapid in the 180-second bout, and a similar end-exercise VO$_2$ will be observed for the 300-second bout. By modifying Equation 3, the CS concept can be used to model interval speed-time performances (dashed curved lines in Figure 3). To derive specific speeds for running-specific interval training times, the following equation may be used:

$$\text{Interval } S = (D' \times 0.6)/t_{1, LM} + CS \quad \text{(Eq 6)}$$

One should note that the speeds for HIIT bouts on a treadmill should be adjusted when relying upon an overground running 3 MT. Specific considerations exist for speed and grade. A previously published conversion table of outdoor speed in comparison with treadmill speed and grade is available, and we have used this table successfully when prescribing treadmill HIIT bouts based on an overground running 3 MT.

When implementing HIIT bouts for an entire team, the CS concept enables standardizing the rest intervals. For example, as shown in Figure 3, 1 group of athletes running a full 300 seconds (Figure 3[B]) is focusing on improving CS without regard for $D'$. Conversely, a second group of athletes are running 180-second intervals (Figure 3[A]) with the goal of improving CS with minimal decline in $D'$. As each group is depleting 60% of $D'$, the same time for the rest interval would be prescribed (eg, 300 s); however, the work:rest ratio would vary. By enabling similar rest intervals, the...
rise in VO$_2$ toward VO$_2$max for each interval will be similar between groups despite different speed-time configurations.$^{23}$

To date, the HIIT prescriptions evaluated by our laboratory have been confined to 60%, 70%, and 80% D' depletion schemes between 90 and 300 seconds. Intervals exceeding 300 seconds are too slow for training in the severe exercise domain (ie, too slow to evoke VO$_2$max).$^{12,25}$ Conversely, intervals shorter than 90 seconds exceed the limit of the CS concept. That is, the speeds prescribed for HIIT bouts <90 seconds may cause fatigue before the body's ability to expend $D'$ and for VO$_2$ kinetics to reach VO$_2$max due to muscular acidosis.$^{26}$

For 60% $D'$ depletion, 4 to 5 intervals between 90 and 300 seconds are recommended (4 bouts when starting out), with a 1:1 work:rest ratio. For 80% $D'$ depletion, 3 intervals between 90 and 300 seconds are recommended, with 1:1.5 work:rest ratio.$^{6}$ Although we have used 70% $D'$ depletion intervals, the sensitivity of the CS concept may exceed 10% (ie, the metabolic responses evoked by 70% and 80% expenditure do not differ).$^{21}$ Indeed, the test–retest reliability may be as high as 20%,$^{2}$ and although 70% and 80% intervals can be prescribed, mathematically, that difference in intensity is unlikely to evoke notably different metabolic responses. However, such observations were confined to cycle ergometry and may not extend to running. Moreover, subjects with higher $D'$ values may be better able to comply with these HIIT prescriptions. Finally, HIIT bouts >80% $D'$ depletion are not recommended, because considering that up to 20% variance in $D'$ is possible, fatigue may occur very early on for bouts exceeding 80% $D'$ depletion.$^{23}$

The prescription of 3- to 5-minute HIIT bouts tends to favor gains in CS$^6$ and VO$_2$max,$^{28}$ but does so at the expense of $D'$ (ie, $D'$ declines). Bouts of 90 seconds yield smaller gains in CS with the preservation of $D'$,$^{6}$ and such bouts may appeal to athletes seeking to improve endurance without compromising sprinting capacity. A total of 4 weeks is sufficient to recognize training gains with previously trained athletes, and retesting of the 3 MT may be necessary to adjust HIIT prescriptions.

Cross-sectionally, $D'$ may have a strength component, in that athletes engaging in anaerobic sports tend to have superior $D'$, or W' in cycling.$^{1}$ Indeed, 2 separate investigative groups have observed that a resistance exercise program improved their $t_{LIM}$ for severe exercise; yet improvements were attributed to gains in W' with no change in CP.$^{20,30}$ The CS concept offers an opportunity to systematically explore the combined effects of aerobic and anaerobic training, on overall performance. More work is needed on the dose-response relationship of HIIT on CS parameters.

Some athletes may have trouble making their prescribed interval times with the previously described methods. If running outdoors, aspects such as head winds and changes in gradient may reduce performance and should be considered when using the CS concept to prescribe intervals. If athletes continue to experience difficulty complying with the HIIT prescriptions, it may be necessary to readadminister the 3 MT. A final consideration is that the method provides speeds or times for intervals specific to the fitness level of each athlete. When a team of athletes is following these prescriptions, each athlete should experience a similar level of fatigue upon completion of each interval. As opposed to prescribing intervals as a percentage of maximum, the use of heart rate monitoring enables the sport scientist to evaluate the time-dependent increases in heart rate that are characteristic of exercise intervals in the severe domain.$^{8}$ The mainstream view of HIIT has focused on repetitive all-out regimes, which involve declining intensities with each interval.$^{32}$ Such HIIT regimes have come under scrutiny for adherence.$^{33}$ Conversely, times for intervals, or interval lap times, using Equations 5 and 6, provide quantitative goals that are challenging yet attainable.$^{6}$ By providing HIIT prescriptions with a quantitative goal, rooted in metrics of the CS concept, adherence for HIIT may be better for athletes and the general population alike.

Conclusions

The 3 MT provides an estimate of CS and $D'$ on a group of athletes in a short period of time. Speed-time or distance-time profiles can be modeled using either previous PR data or by using the results of a running 3 MT. Information from the 3 MT identifies the mechanical measure associated with the maximal VO$_2$ steady state (ie, CS) and the capacity for running at speeds exceeding CS (ie, $D'$).$^{4}$ Using Equation 2, race times associated specific distances may be estimated. Competing runners may be compared using their CS and $D'$, and such comparisons may inform racing strategy (eg, a runner with a superior CS should adopt a front running strategy).$^{12}$ More research is needed on CS and $D'$ normative values for a wider range of athletes, sports, and demographic information (eg, competitive level, gender, and playing position). Such information would inform HIIT training goals (eg, What value of $D'$ should a professional male rugby player be striving for?). Finally, the CS concept is a useful method for prescribing and evaluating the effects of HIIT. Prescribing HIIT using the CS concept allows for the consideration of an athlete's $D'$, a procedure that is a departure from methods of prescription based solely on percentages of maximal aerobic power. The CS concept offers a unique procedure for developing conditioning programs for middle-distance runners and team-sport athletes, but may prove to have utility in other areas.

References


