Methodological Approaches and Related Challenges Associated with the Determination of Critical Power and Curvature Constant

Daniel Muniz-Pumares, Bettina Karsten, Christoph Triska, and Mark Glaister

Abstract

Muniz-Pumares, D, Karsten, B, Triska, C, and Glaister, M. Methodological approaches and related challenges associated with the determination of critical power and W'...J Strength Cond Res 33(2): 584–596, 2019—The relationship between exercise intensity and time to task failure (P-T relationship) is hyperbolic, and characterized by its asymptote (critical power [CP]) and curvature constant (W'). The determination of these parameters is of interest for researchers and practitioners, but the testing protocol for CP and W' determination has not yet been standardized. Conventionally, a series of constant work rate (CWR) tests to task failure have been used to construct the P-T relationship. However, the duration, number, and recovery between predictive CWR and the mathematical model (hyperbolic or derived linear models) are known to affect CP and W'. Moreover, repeating CWR may be deemed as a cumbersome and impractical protocol. Recently, CP and W' have been determined in field and laboratory settings using time trials, but the validity of these methods has raised concerns. Alternatively, a 3-minute all-out test (3MT) has been suggested, as it provides a simpler method for the determination of CP and W', whereby power output at the end of the test represents CP, and the amount of work performed above this end-test power equates to W'. However, the 3MT still requires an initial incremental test and may overestimate CP. The aim of this review is, therefore, to appraise current methods to estimate CP and W', providing guidelines and suggestions for future research where appropriate.

Key Words exercise tolerance, exercise domains, fitness testing, performance, fatigue

Introduction

The relationship between exercise intensity and time to task failure (Tlim) (i.e., the P-T relationship) has received extensive research attention. The first attempts to describe the P-T relationship date back to the beginning of the 20th century when Kenneth (71) and Hill (52) studied the speed of humans and animals over various distances. However, Scherrer and Monod (95) formally described the P-T relationship as hyperbolic in a single-joint muscle action. The P-T relationship seems to be highly conserved and has subsequently been observed in various forms of whole-body exercise, in individuals with different levels of fitness and across animal species (91).

The hyperbolic P-T relationship is characterized by 2 parameters. The asymptote of the hyperbola is defined as critical power (CP), and the curvature constant is notionally abbreviated as W'. Briefly, it has been suggested that CP demarcates the highest exercise intensity at which metabolic and systemic responses attain a steady state (63,91,92). Where power is directly measurable (e.g., cycling), CP is typically expressed as a mechanical power output (PO). However, factors that affect the relationship between oxygen consumption (VO2) and PO, such as cadence, are known to also affect CP (8), and indeed, some authors have proposed to use the term “critical intensity” and to express CP as a VO2 equivalent (117). However, as expressing CP as a PO may be more applicable (87) and freely chosen cadence is relatively consistent within individuals (49), this review will consider CP as a mechanical PO. Regarding W', it represents the amount of work that can be performed above CP and was originally considered to represent anaerobic energy production (53,82). However, it is now accepted that the precise etiology of W' is more complex, and affected by factors such as accumulation/depletion of intramuscular substrates and fatigue-related metabolites (91). Further details on the etiology of CP and W' are discussed elsewhere (61,91,108).
The determination of CP and \( W' \) is of interest to researchers and practitioners alike. For instance, prescribing exercise intensities relative to CP may elicit a more homogenous response than other approaches to normalize the intensity of exercise, such as a percentage of maximum oxygen consumption (\( \dot{V}O_{2\text{max}} \)) (4,73,75). Second, exercise within the “severe” domain, above CP, results in a progressive depletion of \( W' \), so that when \( W' \) is depleted, exercise is either terminated or the intensity reduced to \(<CP\). The determination of CP and \( W' \) therefore allows for prediction of the time to reach \( T_{\text{lim}} \) during exercise above CP. These predictions are typically within 15% of the actual \( T_{\text{lim}} \), and actual and predicted \( T_{\text{lim}} \) are strongly correlated (\( r \approx 0.87 \)) (29,43,64,70,85,88,114). Third, CP is strongly correlated with the running equivalent of CP \( (V_{\text{PO}}) \) and the inverse of \( T_{\text{lim}} \) \( (T_{\text{lim}}^{-1}) \) can be calculated (Table 1), with subsequent linear and nonlinear models applied to estimate CP and \( W' \) (45,51,53,62,82).

Power output and \( T_{\text{lim}} \) derived from each CWR can be fitted using a hyperbolic function (Figure 1A). The asymptote of the hyperbola represents CP, and the curvature constant denotes \( W' \). For any given \( PO \) above CP, the duration of exercise to task failure \( (i.e., T_{\text{lim}}) \) is determined as:

\[
T_{\text{lim}} = \frac{W'}{PO-CP}.
\]  

(1)

The nonlinear equation 1 can be rearranged to a linear function by plotting \( PO \) against the inverse time \( (T_{\text{lim}}^{-1}) \). Here, the slope of the line represents \( W' \), and the \( y \)-intercept represents CP (Panel 1B):

\[
PO = CP + W' \times T_{\text{lim}}^{-1}.
\]  

(2)

An alternative linear function of the \( P-T \) relationship may be obtained by plotting the work accomplished in each CWR against \( T_{\text{lim}} \) (Figure 1C). The \( y \)-intercept of this line represents \( W' \), and the slope represents CP:

\[
\text{Work} = W' + CP \times T_{\text{lim}}.
\]  

(3)

Fitting the \( P-T \) relationship with a 2-parameter function \( (\text{nonlinear} \ or \ \text{derived linear functions}) \) has some limitations. For instance, as \( T_{\text{lim}} \) approaches zero, \( PO \) becomes infinite. To overcome this limitation, a third parameter, \( k \), has been introduced (81):

\[
T_{\text{lim}} = \left( \frac{W'}{PO-CP} \right) + k.
\]  

(4)

**Table 1.** Example of data collected from 5 constant work rate bouts to task failure in a trained cyclist.*

| Trial | Power (W) | Duration (s) | Work (kJ) | Time \(^{-1}\) (s\(^{-1}\)) |
|-------|-----------|--------------|-----------|------------------|
| 1     | 415       | 135          | 56.03     | 0.0074           |
| 2     | 360       | 240          | 86.40     | 0.0042           |
| 3     | 340       | 408          | 138.72    | 0.0025           |
| 4     | 320       | 600          | 192.00    | 0.0017           |
| 5     | 310       | 930          | 288.30    | 0.0011           |
| Max   | 1,100     |              |           |                  |

*Power and duration are recorded during the test, and work and time \(^{-1}\) subsequently calculated. *Max* represents peak power output.

**CONVENTIONAL APPROACH TO DETERMINE CRITICAL
POWER AND \( W' \): MATHEMATICAL MODELS, AND
DURATION, NUMBER, AND RECOVERY BETWEEN TESTS**

The conventional approach to determine CP and \( W' \) in a laboratory setting requires the performance of 3–5 CWR,
where \( k \) is interpreted as the maximum instantaneous PO (PO\(_{\text{max}}\)). Hence, with the inclusion of \( k \), as \( T_{\text{lim}} \) approaches zero, PO approaches PO\(_{\text{max}}\). Critical power and \( W' \) can be determined from a 3-parameter model, in which \( k \) is substituted as:

\[
T_{\text{lim}} = (-\frac{W'}{\text{PO} - \text{CP}}) + (-\frac{W'}{\text{CP} - \text{PO}_{\text{max}}}).
\]  

Another limitation of 2-parameter models is the assumption that for any intensity below CP, there is no contribution of \( W' \) at the onset of exercise. However, with a demonstrated link between CP and \( \dot{V}O_2 \) on kinetics (48,84), some authors have suggested that \( W' \) contribution at the onset of exercise may be somewhat underestimated (62,83). Wilkie (116) proposed accounting for \( \dot{V}O_2 \) on kinetics through the use of a rather fast time constant of 10 seconds for all individuals.

Although the inclusion of the time constant of \( \dot{V}O_2 \) on kinetics appears to be physiologically sound, it seems a cumbersome addition and is currently not used. Further research may investigate whether the inclusion of an individually derived time constant improves the precision of CP and \( W' \) estimations.

An area of concern is the test-retest reliability of the estimates of CP and \( W' \) derived from CWR. Using the linear \( T_{\text{lim}}^{-1} \) model (equation 2), the coefficient of variation (CV) and correlation coefficient (\( r \)) of CP have been reported at 3% and 0.96, respectively, whereas the corresponding values for \( W' \) were 10.3% and 0.79, respectively (46). It is worth noting that a 10–15% variability in \( T_{\text{lim}} \) has been observed in CWR (5,74,83). A large variation in \( W' \) may occur as a result of the nature of the mathematical model because small changes in \( T_{\text{lim}} \) during exhaustive CWR have a negligible effect on CP but a much larger effect on \( W' \) (93,105,107).
Nonetheless, the test-retest reliability seems to be poorer for $W'$ than CP using other methodological approaches (e.g., TT or all-out tests, see discussion below). Furthermore, studies comparing different approaches to determine CP and $W'$ typically report a closer agreement between methods for estimating CP than for $W'$ (67,86,96,103,109),(119), although a high reliability for both parameter estimates (intraclass correlation coefficient of 0.94 and 0.95 for CP and $W'$, respectively) was reported after a familiarization trial when using TT under controlled laboratory conditions (103). Overall, however, $W'$ appears to exhibit a greater variability than CP, although the reason(s) for this phenomenon are not yet completely understood.

Effect of the Mathematical Modeling on Critical Power and $W'$ Estimations

The equations described above typically fit the data with a high degree of accuracy ($R^2 \geq 0.82$) (14,23,45). However, they result in different estimations of CP and $W'$, although equations 1-3 are mathematically equivalent (14,19,20,22,23,45,58,94). Depending on the model, estimations of CP typically are, from highest to lowest, in the following order: linear $T_{lim}^{-1}$ model (equation 2), linear total work model (equation 3), 2-parameter hyperbolic model (equation 1), and 3-parameter model (equation 5), with estimations of $W'$ following the reverse order (Figure 2). It is important to note that in some studies, no differences between mathematical models were reported (19,31,105). Nonetheless, irrespective of whether estimations of CP derived from different mathematical models reach statistical significance, large $T_{lim}$ differences have been observed during exercise at respective CP intensities, ranging ~20–60 minutes (21,23,53,78,86,88).

The question of which mathematical model should be used to determine CP and $W'$ remains unresolved. The 3-parameter model consistently produces lower estimates of CP and greater estimates of $W'$ than 2-parameter models (14,20,22,28,45). Furthermore, the 3-parameter protocol, suggested by Morton (81), requires a relatively large number of trials, including some with low (<1 minute) and high (>15 minutes) $T_{lim}$, which in turn can affect the estimation of CP and $W'$ (see Effect of Duration of Predictive Trials on Critical Power and $W'$). Moreover, the 3-parameter model may produce nonphysiological estimates of $P_{Omax}$, and the parameter exhibits large intersubject variability (28,45,81). These issues may explain why most recent studies have indeed used 2-parameter models (63,65,80,92). An alternative approach has been proposed by Hill (53), and recently adopted by some researchers (18,19,101), whereby the model producing the lowest standard error of estimate (SEE) is used. We therefore recommend that the $P-T$ relationship should be characterized with the 2-parameter model that results in the lowest SEE.

Effect of Duration of Predictive Trials on Critical Power and $W'$

The characteristics of the tests used to define the $P-T$ relationship have a profound effect on CP and $W'$ estimates. For instance, the duration of CWR is known to affect CP and $W'$ estimates. If data from 5 tests to task failure are rearranged, and only the 3 tests with the shortest durations are considered, CP has been shown to be 14–20% greater than that derived from the 3 longest durations, irrespective of the overall range of duration of all 5 exhaustive CWR (16,59). Moreover, $W'$ appears to be notably more sensitive to the duration of the trials, with the 3 shortest exhaustive trials producing $W'$ estimates ~70% greater than those derived from the 3 longest trials (16). The effect of trial duration on CP and $W'$ is shown in Figure 3.

Scherrer and Monod (95) stipulated that the work-$T_{lim}$ relationship (equation 3) loses linearity for exercise durations <2 minutes, with di Prampero (93) specifying that the range of test durations should be such that $V_{O_{max}}$ is elicited, and that $W'$ is fully depleted during each trial. However, the first requirement is not always verified (50,55,76,82), and
a complete depletion of $W'$ may be difficult to assess. At very high intensities (i.e., short $T_{\lim}$), $W'$ may contribute more than the model predicts due to the relatively slow increase in $V_O_2$ (16,82,107). Moreover, at such high intensities, it is possible that exercise terminates before $V_O_2\text{max}$ has been reached (27,54,93,105). Therefore, trials with a $T_{\lim}$ <2 minutes should be considered too short and not included in the determination of CP and $W'$ (16,62,92,93). On the other hand, exercise performed above CP and continued for >2 minutes should lead to maximal values of $V_O_2$ and blood lactate concentration (19,25,89). However, some studies have reported that $V_O_2\text{max}$ did not reach its maximum at task failure during the longest predictive trials, which correspond to intensities slightly (~10%) above CP (11,94). The reason(s) for this phenomenon remain unknown, but it is likely to be multifactorial, including physiological and psychophysiological factors (1,11,94). Therefore, it is recommended that exhaustive trials which result in $T_{\lim}$ >15 minutes should be avoided, as $V_O_2\text{max}$ may not be reached. Furthermore, whenever possible, and at least for research purposes, we recommend that the attainment of $V_O_2\text{max}$ should be verified for all predictive trials.

The range in the duration of the trials should also be considered when investigating alternative testing protocols (i.e., duration of criterion vs. experimental trials) (104). To minimize such effects, it is now common that CP and $W'$ are determined from trials with $T_{\lim}$ ranging between 2 and 15 minutes, with a minimum of at least 5 minutes between the longest and shortest trials (69,105,112). Nonetheless, it has been shown recently that the duration of the predictive trials may still affect the estimation of CP and $W'$, even when these trials are performed within the recommended $T_{\lim}$ range of 2–15 minutes. Triska et al. (102) determined CS and $D'$ from 2 protocols: 3 TT of 12, 7, and 3 minutes and 3 TT of 10, 5, and 2 minutes. The former protocol resulted in ~3% lower CS and ~14% higher $D'$ compared with the latter protocol. It is unclear whether these findings can be extrapolated to other forms of exercise such as cycling, but these data suggest that a consistent protocol should be used to assess or monitor performance using the CP model.

In summary, 2–15 minutes is the recommended duration of trials, and exhaustive trials resulting in a $T_{\lim}$ <2 minutes or >15 minutes should be excluded from calculations. The specific duration of predictive trials should also be considered, even if the overall range of durations falls within the target of 2–15 minutes. Alternatively, research investigating the effects of a treatment may use the same duration (i.e., TT). Furthermore, the attainment of $V_O_2\text{max}$ should be verified wherever possible before including respective trials in the calculation of CP and $W'$.

**Effect of the Number of Trials on Critical Power and $W'$**

Critical power and $W'$ can be determined from just 2 trials. Indeed, CP determined from 2 exhaustive trials with relatively different $T_{\lim}$ (>15 minutes) was only ~1.1% greater than that determined using 4 trials (57). More recently, Simpson and Kordi (97) determined CP and $W'$ in experienced cyclists using a protocol consisting of 2 laboratory-based TT of 3 and 12 minutes, interspersed with 40 minutes of passive rest. The authors noted that after 2 familiarization sessions, the addition of a third trial of intermediate duration (5 minutes) did not affect CP or $W'$. A potential limitation of this approach is that using only 2 exhaustive trials always results in a perfect fitting of the model, and therefore, SEE cannot be determined. Instead, to ensure a high quality of the model, particularly for research purposes, the $P-T$ relationship is most commonly determined from 3 or more CWR to task failure (53). Indeed, a recent approach proposes performing trials until the model falls within a certain SEE, for example, less than 2% (36,92,102) or 5% (18,19) for CP, and less than 10% for $W'$ (18,19,36,42,102). In summary, using only 2 exhaustive trials may seem an attractive option to determine CP and $W'$ in the interest of a short protocol. However, where possible and at least for research purposes, we recommend using 3 or more trials, so that the $P-T$ relationship provides estimates within predetermined SEE's for CP and $W'$.

**Duration of the Recovery Between Exhaustive Trials**

The duration of the recovery between exhaustive trials is usually at least 24 hours, which makes the determination of the $P-T$ relationship cumbersome. To address this issue, some authors have investigated whether a shorter recovery between trials affects CP and $W'$ (15,47,65,86,97,105). Karsten et al. (66) compared the conventional 24-hour method with 2 experimental recovery durations of 3 hours and 30 minutes. The authors observed that in comparison with the standard 24-hour recovery protocol, the 2 shorter recovery protocols were sufficient to not affect CP (prediction error of 2.5 and 3.7% for the 3-hour and 30-minute recovery protocols, respectively, compared with 24 hours). However, the prediction error inherent in the experimental protocols was higher for $W'$ (25.6 and 32.9% for the 3-hour and the 30-minute protocols, respectively). The authors proposed a couple of reasons to explain these findings. First, the shorter recovery protocols might have led to only a partial reconstitution of $W'$, although $W'$ may be restored within ~25 minutes after exhaustive exercise (33,41,98). Second, high-intensity exercise can affect the $V_O_2$ on kinetics and increase (i.e., "prime") performance in subsequent exercise performed up to 45 minutes after the initial bout (3,24). However, Karsten et al. (65) more recently showed that $V_O_2$ on kinetics were not significantly different between repeated CWR and TT after a 60-minute recovery period, suggesting that at least for the 3-hour recovery intervention, the argument does not hold. In summary, a single-day determination of CP can be achieved by reducing the intertrial recovery time to 30 minutes. However, at present, a more conservative recovery of 60 minutes is preferred to
Determination of Critical Power and W' Using Time Trials Under Laboratory and Field Conditions

Laboratory and Field Determination of Critical Power and W'

With the popularization of power meters, PO data are readily available, which allows for analysis of the P-T relationship in the field. For instance, PO data from elite cyclists over a competitive season have been reported for exercise durations ranging from 1 second to 4 hours and, unsurprisingly, mean PO decreases nonlinearly as the duration increases (90). Indeed, a translation of laboratory-based determination of CP and W' into the field was attempted by Karsten et al. (67). The study compared CP and W' results, using 3 laboratory CWR (resulting in task failure times of ~12, 4, and 2.5 minutes), with those determined from 3 track-based TT where participants had to produce the highest possible PO for 12, 7, and 3 minutes. All tests were performed on separate days, and the authors reported a close agreement between laboratory and field CP values (prediction error of 7 W). However, field values of W' were ~5 kJ higher than those obtained in the laboratory, irrespective of the mathematical model used. In a follow-up study (69), a shortened testing protocol (i.e., a 30-minute intratrial recovery period; see Duration of the Recovery Between Exhaustive Trials) was used to investigate whether CP and W' could be reliably determined from road PO data. The study comprised 3 experimental protocols and a criterion protocol to determine CP and W'. The criterion protocol consisted of 3 laboratory-based CWR interspersed with 30-minute recovery, and the experimental protocols were: i) a TT field-based protocol consisting of 3 maximal exhaustive efforts over 12, 7, and 3 minutes, interspersed with 30-minute recovery; ii) a field-based protocol consisting of 3 TT over the same durations but interspersed with 24-hour recovery; and iii) unintentional TT maximal efforts (i.e., highest PO over the 3 durations obtained at any point during a single training session). The results demonstrated a high agreement for all experimental CP values with a mean prediction error of ~11, 17, and 14 W for protocols i, ii, and iii, respectively. However, results for W' showed an acceptably high prediction error of ~3, 4, and 3 kJ, respectively. All experimental protocols were repeated 3 times with a mean within-protocol CV for CP of 2.4, 6.5, and 3.5%, respectively. Of note is that protocol ii is at the upper end of what is considered as acceptable reliability for physiological variables in sports science research (2,56). Regarding W', only protocol iii, the unintentional efforts, provided a relatively low CV for W' (~17%) when compared with protocol i (~46%) and protocol ii (~45%). Triska et al. (105) compared a single-day field test to estimate CP and W' (3 TT of 12, 6, and 2 minutes) with a laboratory-based protocol using a cadence-dependent (i.e., linear) mode to mimic “real-world” exercise. The authors reported similar mean values between conditions for CP (laboratory: ~280 W vs. field: ~281 W) and a 95% limits of agreement (LoA) of ~55 to 50 W. By contrast, W' was significantly higher under laboratory conditions (~21.6 vs. ~16.3 kJ) with a correspondingly poor agreement (95% LoA: ~3.5 to 16.4 kJ) between protocols. Altogether, these data suggest that CP can be determined with reasonable precision in the field or by simulating field conditions (i.e., using TT). However, W' appears to be underestimated (single-day approach (105)) or overestimated (multiday approach (67)) using these tests, although reasons have not yet been elucidated.

Time Trial vs. Constant Work Rate Tests

There are a number of methodological differences between laboratory- and field-based tests that need to be considered within the context of CP and W' determination. First, laboratory-based protocols typically use open-end tests (i.e., CWR), whereas field tests typically use maximal effort over a fixed time or distance (i.e., TT). Time trials exhibit less test-retest variation than CWR (74) and therefore resulting in significantly lower SEE for CP and W' estimates (65). Second, TT are self-paced, and pacing has been shown to affect the P-T relationship (18,64). Black et al. (18) compared estimations of CP and W' derived from 4 to 6 CWR prediction trials performed on different days with work-matched TT in the laboratory. Despite being equaled for work, mean PO was higher, and therefore Tlim shorter during TT, possibly due to the fast start commonly adopted in TT (18). As a result, CP was ~7% higher using TT, whereas W' was not affected by the type of exhaustive trials, although there was a negative correlation (r = -0.74) between the relative change in CP and W' in CWR and TT (18). By contrast, Karsten et al. (65) compared non time-matched CWR with TT in the laboratory, with a recovery time of 60 minutes between efforts to avoid a possible VO2 priming effect evident with shorter recovery periods (see Duration of the Recovery Between Exhaustive Trials). The results demonstrated a low prediction error for CP (2.7%; 8 W), but a high prediction error for W' (18.8%; 2.5 kJ), although it is likely that the latter was influenced by the relatively short recovery period between efforts. It is also worth noting that Black et al. (18) used self-paced TT, where the ergometer was set in linear mode with a fixed resistance (i.e., cadence-dependent mode) allowing PO to be regulated by cadence only, whereas Karsten et al. (65) used self-paced TT, where the ergometer allowed PO to be self-regulated using changes in gear ratio (virtual) and cadence, in an attempt to better replicate real-world cycling. Third, TT are not constrained by cadence, whereas CWR are commonly performed at a predetermined cadence (105), and pedaling rate is known to affect CP and W' (8,34,75,110). Fourth, the duration of CWR is variable, whereas it can be standardized for TT. As a result, there might be differences in the duration of exhaustive trials (18), which, as discussed above, can affect CP and
Critical Power and W’ Determination

W’. Further evidence for the effects of time differences also comes from other exercise modes. In running, Galbraith et al. (47) reported that estimations of CS derived from 3 TT interspersed with either 30 or 60 minutes of passive rest between trials were not significantly different from 3 CWR performed in the laboratory using a multiday protocol (typical error 0.14 and 0.16 m s\(^{-1}\) for 30- or 60-minute rest, respectively). By contrast, field-based estimations of D’ were significantly lower (typical error 88 and 84 m for 30- or 60-minute rest protocols, respectively) than those derived from a laboratory-based test. The field-based approach also exhibited comparable test-retest variability with that obtained from the conventional laboratory-based approach (0.4 and 13% for CS and D’, respectively). Triska et al. (104) attempted to address the issues surrounding the values of D’ by time-matching the laboratory and the field trial durations. The authors reported no differences and positive correlations for CS and D’ between the 2 conditions, and LoA of \(\pm 0.24\) m s\(^{-1}\) and \(\pm 75.5\) m. These studies seem to indicate that reasons other than that of trial duration are responsible for the conundrum surrounding D’. Fifth, there appear to be a number of factors during field-based TT protocols that might affect CP and W’ such as standing vs. rolling starts, overcoming inertia and acceleration, increased air resistance, or differences in terrain (79,89,105). The precise role of each of these factors warrants further investigation. On the other hand, field-based tests can offer a more ecologically valid approach to estimate CP and W’. This is particularly true if CP and W’ are to be used in the field, where the above issues of acceleration, pacing or air resistance, remain present. A final point to consider is the test-retest reliability of estimations of CP and W’ using TT. Recently, Triska et al. (103) performed 3 identical TT to determine CP and W’ using a single-day protocol with the first TT used as familiarization. The authors noted that the CV of CP and W’ between the familiarization and the first subsequent TT were 4.1 and 25.3%, respectively. However, the analysis of the 2 consecutive TT performed after familiarization produced closer estimates in both CP and W’ (2.6 and 8.2%, respectively). Therefore, the authors concluded that familiarization is advisable to determine CP and W’ from TT using a single-day protocol.

In summary, although laboratory-based TT can be used to determine CP and W’, some discrepancies in the estimation of CP and, in particular, W’ are evident. Nonetheless, and although there are methodological differences between CWR and TT protocols, TT may be preferable over CWR, particularly if the data are to be used under field conditions. If CP and W’ are determined from TT, performing a familiarization trial is advisable to increase the reliability of the estimates.

The 3-Minute All-Out Test

The conventional approach to determine CP and W’ requires the performance of repeated maximal efforts, which may compromise the practical application of the model. It has been hypothesized that the parameters of the \(P\)-\(T\) relationship may be obtained from a single all-out test. The rationale is that at the start of all-out efforts, W’ is heavily used; however, as the exercise continues and PO decreases, so does W’. If the duration of exercise is sufficiently long, W’ becomes fully depleted and, therefore, the PO at or toward the end of an all-out effort should represent CP. Dekere et al. (35) first explored this idea using an all-out effort lasting 90 seconds, but the authors noted that at the end of the test, PO was greater than CP, and that W’ was not fully depleted. Burnley et al. (25) extended the duration to 180 seconds and observed that the decrease in PO had stabilized in the final 30 seconds of the test (defined as “end-test PO” [EP]) (Figure 4). In a follow-up study, a close agreement was reported between the conventionally determined CP and the EP obtained during a 3MT (\(r = 0.99\); SEE = 6.4 W) (109). Moreover, the work performed above EP (WEP) was similar to W’ (\(r = 0.84\); SEE = 2.6 kJ). For the purpose of this review, we will use CP and W’ when referring to results derived from the conventional approach using CWR or TT, and EP and WEP when referring to the 3MT.

The original 3MT still requires 2 testing days, as a prior exhaustive incremental maximal test is a prerequisite for the subsequent ergometer setting, using values of gas exchange threshold (GET), preferred cadence, and \(\text{VO}_2\max\) (25,109). The 3MT starts with a period of unloaded cycling after which participants are instructed to accelerate their cadence up to 110–120 rpm at which point the cycle ergometer switches into the linear mode. The linear factor is set so that at the participant’s preferred cadence, the PO corresponds to halfway between GET and \(\text{VO}_2\max\) (50%\(\Delta\); equation 6), which is suggested to approximate CP (25): \[
\text{Linear factor} = \frac{\text{PO at } 50\%\Delta}{\text{Cadence}^2}.
\] (6)

As fatigue develops during all-out exercise, cadence drops resulting in a decline in PO and the typical curvilinear 3MT power profile. To prevent pacing, participants are blinded to elapsed time, and strong verbal encouragement is required throughout the test. To provide reliable results, a familiarization 3MT trial is also commonly performed, increasing the overall time required to determine EP and WEP. Performing an exhaustive incremental maximal test, a familiarization trial and the actual 3MT necessitates more than one laboratory visit, which in turn lengthens a protocol that benefits from an otherwise short testing methodology.

There are no formal criteria to verify the validity of the 3MT. However, some authors reported that PO plateaus toward the end of the 3MT, as determined using consecutive 30-second bins (25,44). It has been also reported that PO peaks within the first 10 seconds (109), and subsequently decreases rapidly so that >90% of WEP is depleted within the first 90 seconds of the test (110). In addition, as an all-out
effort is required, a decrease in PO greater than 5% of EP (see discussion below on reliability) for 5 seconds may denote pacing and cause some reconstitution of WEP, and therefore an overestimation of this parameter. An accurate selection of the linear factor is crucial because relatively small alterations in preferred cadence by ±10 rpm can significantly affect EP and WEP and end-test cadence (110). To reflect the maximal (i.e., all-out) nature of the test, VO2 has been suggested to attain its maximum during a 3MT (25,44,109); and blood lactate concentration reaches ≥8 mmol·L⁻¹ (25,110,113). In summary, the following criteria may be proposed to ensure a true 3MT all-out effort: (a) a plateau in PO in the last 30 seconds of the test; (b) the attainment of peak PO within the first 10 seconds of the test; (c) rapid initial decrease of PO, so that >90% of WEP is depleted within the first 90 seconds of the test; (d) no decrease in PO >5% EP for >5 seconds during the test; (e) an end-test cadence within 10 rpm of preferred cadence; (f) the attainment of VO2max; and (g) a blood lactate concentration ≥8 mmol·L⁻¹. Regarding the reliability of EP and WEP, both parameters show a similar degree of reliability to those derived from the conventional testing approach. Specifically, the reliability of EP has consistently been shown to be better (CV of 3–7%) than that of the WEP (8–21%) (25,39,60,75).

Single-Day Alternatives of the Original 3MT
As the original 3MT requires 2 laboratory visits, several authors have attempted to shorten or to simplify the original 3MT. For instance, Johnson et al. (60) proposed that the resistance of the 3MT may be determined relative to body mass, somewhat similar to the Wingate anaerobic test. Bergstrom et al. (10) reported that a modified 3MT, performed on a mechanically braked ergometer, with resistances set at 4.5% body mass, could be used to determine EP and WEP. However, if the resistance was set at 3.5% body mass, the modified 3MT produced different estimates of EP and WEP than those derived from the original 3MT and from the conventional approach (10), although the error was not reported, and agreement between methods was identified using a test of difference. In a similar study, Clark et al. (31) performed a 3MT on a mechanically braked ergometer using loads of 3, 4, or 5% of body mass for recreationally active, anaerobic and aerobic athletes, and endurance athletes, respectively. There were no significant differences in either EP or WEP determined from the 3MT, irrespective of whether values were determined using linear factors based on body mass or using the conventional linear factor of 50% Δ. The authors, however, reported a large individual variation between the methods in estimates of EP and, particularly, WEP (4.2 and 39.4%, respectively). Dicks et al. (39) calculated the linear factor based on age, sex, body mass, and self-reported physical activity levels. The authors reported no differences in either EP or WEP between the original 3MT and the alternative 3MT. Moreover, there were no differences between the parameters of the P-T relationship derived from the alternative 3MT, and those derived from 3 CWR using linear models (Eqs. [2,3]). However, the CV between methods was again much higher for WEP (≥21.8%) than for EP (≤4.8%) (39). In addition, Dicks et al. (39) used CWR lasting ~3, 4, and 5 minutes to model the P-T relationship, possibly overestimating CP and underestimating W’ (see Effect of Duration of Predictive Trials on Critical Power and W’). Constantini et al. (33) evaluated the effects of performing the incremental test and 3MT in a single testing session. The authors reported that a 3MT performed 20 minutes after the incremental test resulted in EP and WEP values similar to those obtained when the 3MT and incremental test were performed over different days (SEE 5 W and 1.81 kJ for EP and WEP, respectively). Clark et al. (30) evaluated the merits of performing a 3MT on the CompuTrainer, a training ergometer often used by cyclists. The results showed a good agreement between conventional (linear work and Tlim⁻¹ models) and 3MT approaches for determining CP and EP (2.8 and 3.1%, respectively). However, a poor agreement between WEP and W’ derived from the linear Work-Tlim (CV of 24.4%) and PO-Tlim⁻¹ (CV of 26.3%) models was also reported.

In summary, various alternatives have been proposed to simplify the conventional 3MT. Overall, alternative approaches of the 3MT discussed above seem to produce...
similar EP values compared with the original 3MT. However, because WEP seems to exhibit large variation, alternative protocols to the 3MT warrant caution, and as such, the conventional 3MT protocol is preferred.

Most of research focusing on the 3MT has been performed in healthy and athletic populations, most likely because of the challenging nature of sustaining an all-out effort for 3 minutes. It is nonetheless worth noting that the 3MT has been performed by adolescents (14–15 years), who might have a reduced anaerobic fitness compared with adults (7). No significant differences were observed between the conventional and 3MT approaches to estimate CP/EP and W’/WEP values in adolescents, although a large variation (~20%) within individuals prevented the 3MT and conventional approaches from being used interchangeably (6). Future research should consider whether the 3MT is a feasible option for nonathletic populations, particularly those with limited fitness.

**Critical Appraisal of the 3-Minute All-Out Test**

Other approaches have been adopted to determine CP and W’ using a 3MT, which provide further insight into the validity of EP and WEP for estimation of CP and W’. For instance, several studies have investigated the 3MT using isokinetic cycling exercise. Dekerle et al. (34) reported that the isokinetic 3MT produced measures of CP and W’ that were not significantly different from those derived using the traditional approach, although the large intrasubject variability, in particular for WEP, led the authors to caution against the use of the isokinetic 3MT. Karsten et al. (68) reported a greater EP (~7%) and smaller WEP (~25%) derived from an isokinetic 3MT than those obtained from the conventional approach, with poor levels of agreement between these 2 approaches. In contrast to the above, Wright et al. (118) conducted the only study to date comparing the conventional CWR with the 3MT method in both linear and isokinetic mode, and reported that the 3MT provided a better agreement in isokinetic mode (LoA = 4 ± 30 W; SEE = 5%) than in linear mode (LoA = 30 ± 47 W; SEE = 8%). Moreover, the authors noted significant differences and low LoA between W and WEP derived from both isokinetic mode 3MT (LoA = 7 ± 9 kJ; SEE = 27%) and linear mode 3MT (LoA = 9 ± 9 kJ; SEE = 26%) (118).

The “gold-standard” approach to determine CP and W’ is still a series of CWR in the laboratory (53,62), and therefore is the method chosen to validate the 3MT (12,96,109,110). However, although several studies have reported a close agreement between traditional and 3MT-derived measures of CP and EP (12,96,109,110), others have reported that EP overestimates CP, irrespective of the mathematical model used to determine CP (9,14,85). Indeed, although exercise at CP can be sustained for >20 minutes, exercise at EP was only maintained for 12–15 minutes (12,13,77). However, EP has demonstrated a strong positive correlation with a various thresholds, such as the lactate threshold ($r = 0.79$), the maximal lactate steady state (MLSS; $r = 0.93$), and the onset of blood lactate accumulation ($r = 0.85$) (100); Black et al. (17) observed that performance in a 16.1-km cycling TT was strongly correlated with EP ($r = 0.83$). However, the PO associated with the MLSS was 24 W (11%) (44) to 54 W (21%) (100) lower than EP. Moreover, the difference between CP and MLSS showed heteroscedasticity, as the difference between these 2 parameters increased in highly trained individuals (100). Indeed, the use of the 3MT has been criticized for elite cyclists as EP overestimated CP by ~50 W, and WEP underestimated W’ by ~8.8 kJ (9). Nonetheless, the 3MT is able to detect changes in CP after 4 weeks of high-intensity training, as both CP and EP increased by a similar ($r = 0.77$) magnitude, and the agreement between CP and EP was good, pre- and post-training (typical error 4.6 and 4.3 W, respectively) (111). Furthermore, Clark et al. (32) demonstrated that a 3MT is able to detect fatigue-induced changes in EP and WEP during prolonged cycling. These authors found that 2 hours of heavy exercise causes a decrease of 8 and 20% for CP and W’, respectively, suggesting that EP and WEP may be able to assess fatigue. In summary, although the 3MT may offer a time-efficient approach to estimate CP and W’ and an ability to monitor training adaptations and fatigue, these studies suggest that a degree of caution is warranted when assuming that EP and WEP represent CP and W’, respectively, particularly in elite athletes.

**Practical Applications**

The nonlinear $P-T$ relationship is well described by a hyperbolic function, which results in 2 parameters: the asymptote (CP) and the curvature constant (W’). Conventionally, several CWR to task failure are required to determine CP and W’, using various modeling techniques. However, the mathematical model used, and the characteristics of the exhaustive trials such as duration, rest between trials, and mode (TT vs. CWR) have been shown to affect CP and W’ estimations. It is recommended that CP and W’ should be determined using the 2-parameter model that results in the lowest SEE. Regarding the exhaustive trials, a minimum of 3 CWR or TT is recommended with a duration spanning 2 minutes to 15 minutes. Trials that fall outside of this time range should not be used to estimate CP and W’, and the attainment of $V_O_2 max$ should be verified where possible. Moreover, if the individual SEE exceeds 2–5% for CP or 10% for W’, further trials should be included in the calculation. Although recovery between exercise bouts of ≥60 minutes appears to be sufficient to avoid $V_O_2$ priming effects, the inability to determine W’ suggests that at present 24-hour recovery periods between trials may be best. The use of TT has recently been used to determine the $P-T$ relationship in the field. Although there are a number of factors that might confound laboratory- vs. field-based tests, such as seating positions, acceleration and inertia, air resistance, or differences in terrain, field tests seem to provide similar CP values.
than those established in the laboratory while also offering an ecologically valid and practical approach to determine CP and W'. Field-based tests can be integrated into daily training, which in turn reduces the need for laboratory access and equipment. Similarly, CP testing in the laboratory can now be performed using TT. However, although this testing method provides highly reliable results for both parameters, it still requires further research to investigate validity of W' values. The 3MT allows for the determination of EP and WEP, which are considered to represent CP and W', respectively. Although a good agreement between estimates of CP and W' derived from the conventional approach and the 3MT has been used to validate the latter, recent research suggests that EP may overestimate CP, especially in elite athletes. The original 3MT requires repeated laboratory visits: an initial exhaustive incremental maximal test to determine GET and VO$_{2}$max, and a subsequent visit to perform the actual 3MT. A number of alternatives have been proposed to further reduce the protocol to a single-day test. Although some of these alternatives have shown good agreement between methods, further research should also investigate the physiological responses at EP, determined from these alternative 3MT protocols. The recommendations given in the current review should be applied to cycling, but, where possible, might be extended to other modes of exercise, such as running, swimming, rowing, or kayaking.

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