Redefining Exhaustion: Considerations for the Modeling of Critical Power

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Abstract

Background: The relationship between exercise intensity and the limit of tolerance is the focus of the Critical Power (CP) model. CP defines the upper limit for which exercise is steady state and is – in theory – indefinitely sustainable. However, this limit of tolerance at CP is often well below 30 min. **Purpose**: We want to test the hypothesis that 1) a clinically significant residual W' capacity (W'_{res}) does exist, 2) that the size of W'_{res} is inversely related to t_{lim} used in the testing protocols, and 3) that accounting for W'_{res} will result in an improved calculation of the Critical Power (CP), as determined by an increased time to exhaustion at CP. **Methods**: Nine well-trained cyclists performed a ramp test and four high-intensity tests to exhaustion on a cycle ergometer to determine CP and the curvature constant (W'). Two tests to exhaustion were then performed at the traditional CP (CP_{trad}) and a novel, modified CP (CP_{mod}) to test the practical significance of the residual capacity on the calculation of the CP. **Results:** All participants were able to perform work above CP even after reaching the limit of tolerance, despite no significant changes in physiological parameters. Including the W'_{res} resulted in significantly lower estimations of CP (TRAD: 281W, MOD: 278 W; $p = 0.015$) and higher estimations of W' (TRAD: 15.8 kJ, MOD: 17.8 kJ; $p = 0.008$). **Significance**: Athletes were able to continue generating power above CP, even after reaching the limit of tolerance. This residual capacity resulted in a significantly lower estimate of CP and significantly higher estimation of W'.

Keywords: Sport science, cycling, fatigue, modeling, Critical Power

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List of Abbreviations

$[La^-]$ – Concentration of Lactate

ANOVA – Analysis of Variance

CP – Critical Power

HR – Heart Rate

kJ – kiloJoules

RPE – Rate of Perceived Exertion

t_{LIM} – Limit of Tolerance

t_{END} – End of test

TTE – Time to Exhaustion

USG – Urine Specific Gravity

$\dot{V}CO_2$ – Rate of Carbon Dioxide production (expressed in L/min)

$\dot{V}_E$ – Rate of Ventilation (expressed in L/min)

$\dot{V}O_2$ – Rate of Oxygen consumption (expressed in L/min)

$\dot{V}O_{2peak}$ – Peak rate of Oxygen consumption (expressed in L/min)

W - Watts

W’ – Curvature Constant

W'_{RES} – Residual W’ Capacity

$Work_{LIM}$ – Work Limit

$Work_{RES}$ – Residual Work Limit

1. Introduction

The capacity for hard exercise is finite for all species. The hyperbolic relationship between intensity above a moderate range and the limit of tolerance (t_{LIM}) was first identified by Nobel Laureate A.V. Hill nearly 100 years ago (Hill 1925). However, the relationship between high intensity performance was not mathematically described for another 40 years by the physiologists Monod & Scherrer (Monod and Scherrer 1965). They determined that the horizontal asymptote of this relationship is the Critical Power (CP), which "represents the highest metabolic rate that a muscle group can sustain for a very long time without fatiguing" (Monod and Scherrer 1965; Moritani et al. 1981; Hill 1993). Additionally, the CP is thought to delineate exercise in the heavy intensity domain, where steady state can be maintained, and the severe intensity domain, where cellular homeostasis is lost and exhaustion ensues (Hill 1993). The second parameter of this mathematical relationship is the W' (pronounced W prime), which is measured in kilojoules (kJ). The W' defines the shape of the curve above CP and represents a finite capacity of work that can be performed above the CP before t_{lim} is reached and exercise must be terminated (Monod and Scherrer 1965; Moritani et al. 1981). The CP and W' are unique for every individual and can be determined by fitting a curve from a series of brief, high-intensity tests to exhaustion.

In athletes, this CP/W' model can provide information about performance capacity. Periodic CP/W' testing can be performed to track fitness progression across training cycles and athletic seasons. The CP concept can also be used by coaches to prepare their athletes for competition. For example, if an athlete's CP and W' are known, it is possible to calculate the t_{LIM}

at any power above CP, or conversely, the highest power that can be sustained for a given amount of time. Since CP separates the heavy and severe intensity exercise domains, it can also be used as a tool for exercise prescription, allowing athletes to train at intensities that will elicit well-reported physiological adaptations in energy supply, cardiorespiratory responses, fatigue responses, and effort perception (Holloszy and Coyle 1984). Sports scientists have also used CP testing as a tool to further understand the physiological effects of ergogenic/nutritional interventions (Miura et al. 2000; Silveira et al. 2018), hypo-/hyperoxia (Moritani et al. 1981; Vanhatalo et al. 2010; Simpson et al. 2015; Townsend et al. 2017), and prior heavy exercise (Ferguson et al. 2007; Clark et al. 2018) on performance capacity. The traditional CP prediction trial testing protocol requires athletes to exercise at a constant workload to exhaustion; at the point of fatigue, the test is ended, and it is assumed that the maximum possible workload at this point decreases instantaneously to CP.

From the current testing protocol, the time to exhaustion at CP is under 30 min (Jenkins and Quigley 1990; Brickley et al. 2002), which is far short of the theoretical definition of a work rate that can be continued “indefinitely” (Monod and Scherrer 1965; Moritani et al. 1981). To reconcile this discrepancy, some researchers have argued for the existence of a residual capacity (W'_{RES}) above CP even upon reaching t_{LIM}, suggesting that the work rate should gradually approach rather than abruptly dropping to CP (Figure 1). As proposed by Saltin & Karlsson, “the higher the power requirement at exhaustion [t_{LIM}], the more it [residual capacity] is that remains” (Saltin and Karlsson 1971). This W'_{RES} is not included in the current CP testing protocols and may play a role in providing a more accurate calculation of an athlete’s maximum sustainable metabolic rate. Since the total work performed during each high intensity test is constant and comprised of work from both CP and W', increasing the capacity of W' (through inclusion of W'$_{RES}$) means that the work rate of CP *must* be lower to maintain a constant amount of work. Shifting the calculation of CP downwards by accounting for W'$_{RES}$ may result in a metabolic work rate that aligns more with the theoretical definition of an indefinitely sustainable work rate. As such, this project has implications for the assessment of fitness and prescription of training that is based upon the calculated CP value.

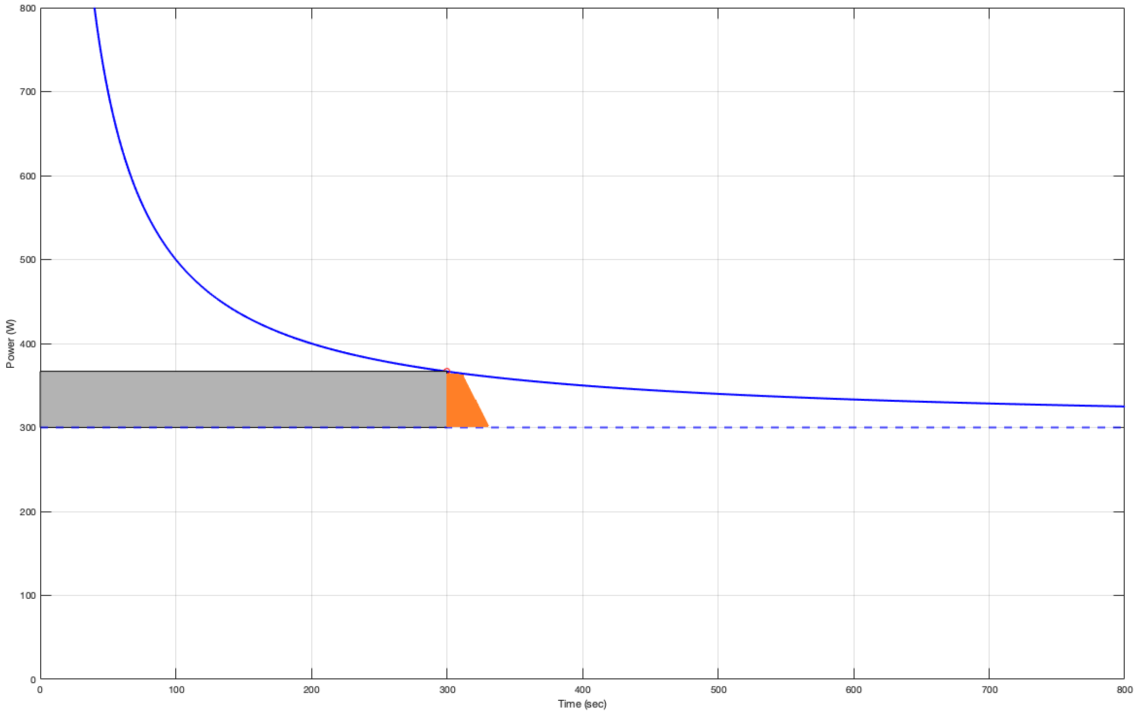


Figure 1. Representative CP/W' curve for an athlete with a CP of 300 W and W' of 20 kJ. The CP is represented by the horizontal dashed blue line, and the size of W' is represented by the gray rectangle, which shows the maximum sustainable power output for 300 s. At the end of the 300 s effort, the current model suggests that the subject's power output must instantaneously decrease to an intensity at or below the CP. The purpose of this study is to test for a residual capacity above CP (W'$_{res}$) following reaching the limit of tolerance, which is illustrated here as the orange area.

Therefore, the purpose of this project is to explore and quantify a potential residual capacity (W'$_{RES}$) in athletes completing CP/W' testing. This will be accomplished using a modification to traditional CP testing protocols, where high-intensity work will continue beyond the initial limit of tolerance has been reached by progressively decreasing the workload. It is hypothesized that: 1) a clinically significant residual W’ capacity does exist, 2) that the size of W'_{RES} is inversely related to t_{LIM} used in the testing protocols, and 3) that accounting for W'_{RES} will result in an improved calculation of the CP, as determined by a significantly lengthened time to exhaustion at CP.

2. Literature Review

A thought-provoking question for any competitive cyclist might be “How long can you sustain a given power output?” The relationship between the intensity of an exercise and the time for which that intensity can be maintained is quite intuitive and has likely been experienced by everyone – i.e. the shorter the duration, the higher the intensity that can be maintained. Although this principle has been understood for thousands of years, the formal scientific investigation and mathematical description of this relationship began only 100 years ago. The first recorded observations were made by A.V. Hill in 1926, who noted that even world record-holding athletes had decreasing speeds when graphed against times for that particular event (e.g., 100 m versus 800 m running events on the track), while sustainable work rates reached practically constant values at durations beyond 12 min (Hill 1925). This phenomenon was repeatable across several species, sports (running, swimming, rowing) and in both men’s and women’s sports. This constant work rate, now known as the critical power (CP), was mathematically determined 40 years later and defined as “the maximum rate that [a muscular group] can keep up for a very long time without fatigue” (Monod and Scherrer 1965). The CP is now considered by many physiologists to be the gold standard of maximal metabolic rate, since it defines the maximum work that separates distinct physiological domains (i.e. steady state v. non steady state) (Jones et al. 2019).

The idea of a Critical Power is built upon strong historical, theoretical, mathematical, and physiological foundations (Hill 1925; Wilkie 1960; Monod and Scherrer 1965; Moritani et al. 1981). The hyperbolic function first discovered by A.V. Hill, now defined by its mathematical asymptote (CP) and curvature constant (W’, pronounced W prime), has been applied to isolated and whole body exercise (Monod and Scherrer 1965; Hughson et al. 1984; Poole et al. 1988a; Burnley 2009), and is considered a fundamental bioenergetic property of animals, having also been described in other species (Full and Herreid 1983; Full 1986; Billat et al. 2005; Lauderdale and Hinchcliff 2010; Copp et al. 2010). Theoretically, the CP represents the highest work rate that can be sustained indefinitely without a progressive loss of homeostasis. Mathematically, CP and W’ are two constants that can be used to calculate the relationship between work rate and the limit of exhaustion. However, unlike previous physiological thresholds that have been proposed (i.e. lactate threshold, respiratory compensation point, etc.), the Critical Power model is unique because it is not defined by any single physiological measure. In fact, the multifaceted nature of fatigue during severe exercise (Fitts 1994; Amann and Calbet 2008) suggests that *any* single physiological index is unlikely to predict the maximal metabolic state. Physiologically, the CP is the boundary between the heavy and severe exercise domains, where the pulmonary gas exchange/ventilation, metabolic, blood acid-base, cardiovascular, and neuromuscular responses are distinctly different, as will be discussed below.

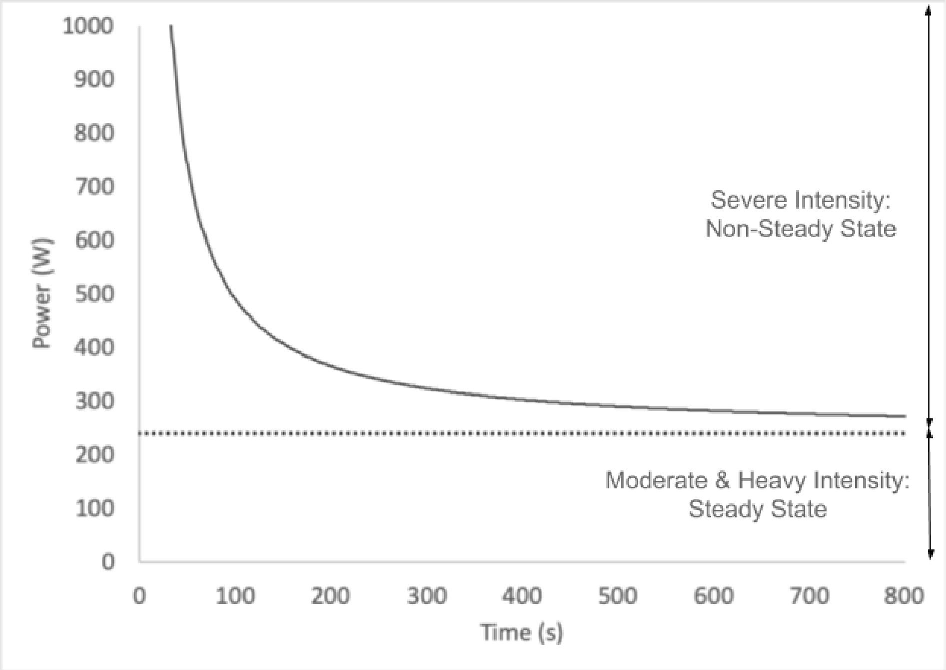


Figure 2. Exercise intensity domains, with an overlaid representative Critical Power Curve. The limit of tolerance (in seconds) is shown along the x axis, and the work rate (in Watts) is shown along the Y axis. The Critical Power (dashed line) is the boundary between steady state exercise (moderate/heavy domains) and non-steady exercise in the severe domain.

2.1.Origins and Development of the CP/W’ Model

In 1965, the physiologists Monod and Scherrer presented for the first time a mathematical solution to the hyperbolic relationship first identified by A.V. Hill. To do this, participants completed several constant-load exercise tests to the limit of tolerance (t_{LIM}). Once the tests were completed, the amount of work performed during each test (in kJ) was plotted against the respective limit of tolerance. What the researchers discovered was a linear relationship between the maximum amount of work that could be performed (work limit; W_{LIM}) and t_{LIM} (Figure 3, Equation 1) (Monod and Scherrer 1965).

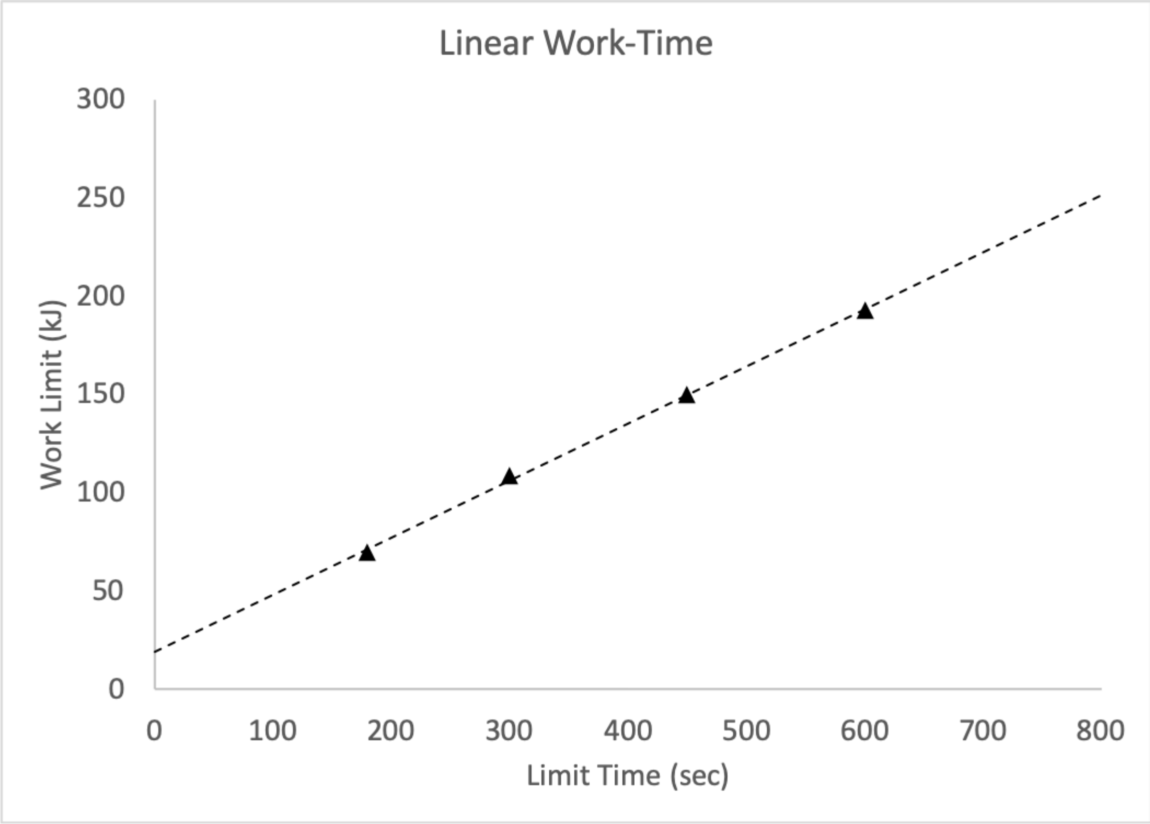


Figure 3. A linear relationship between the work performed and the limit of tolerance can be observed by having participants perform several high intensity exercise tests to exhaustion (each triangle represents an individual test). The slope of this line is the maximum sustainable work rate - CP, and the y-intercept represents the "energetic reserve", now identified as W'.

$$W_{lim} = a + b \cdot t_{lim} \quad (1)$$

The linear equation they derived is rather easy to interpret – the maximum amount of work that can be performed in a given amount of time (W_{LIM}) results from a work rate whose maximum rate is *b* and the use of an "energetic reserve", whose capacity is captured by *a*. They defined this maximal work rate (*b*) as the critical power, which was "the maximum rate that [a muscular group] can keep up for a very long time without fatigue" (p. 329)(Monod and Scherrer 1965). This critical power is similar to the asymptote identified by A.V. Hill. In fact, their discovery was simply an inverse transformation of the hyperbolic relationship observed by Hill (Fig 3, 4).

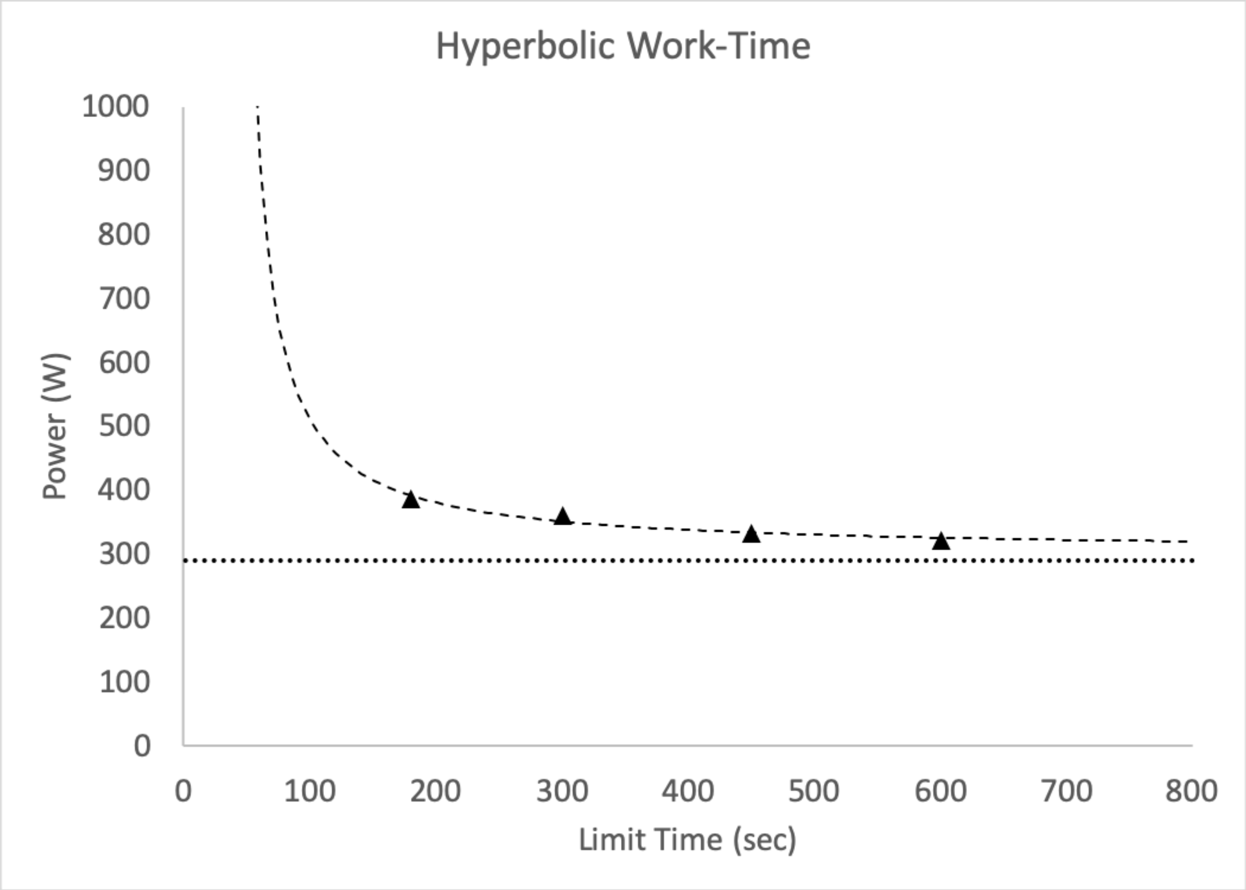


Figure 4. By plotting the intensity of each exercise test (in Watts) against the limit of tolerance (in seconds), the hyperbolic relationship is observed. Note that these are the same four exercise tests used in the linear work-time model (Fig 2). In the linear work-time model, the CP was defined as the slope of the line. In the hyperbolic power-time model, the CP is defined by the horizontal asymptote (dotted line).

2.1.1. Critical Power as a Metabolic Rate

It is important to point out that, in theory, the Critical Power represents the greatest *metabolic* rate, not an external work rate, that results in energy provision predominantly through oxidative metabolism (Monod and Scherrer 1965; Moritani et al. 1981; Hill 1993; Poole et al. 2016). Further support for the oxidative basis of CP lies in the manipulation of the CP upwards with hyperoxia (Vanhatalo et al. 2010), and downwards under hypoxia (Moritani et al. 1981; Simpson et al. 2015; Townsend et al. 2017; Deb et al. 2017).

Although the human body operates on a continuous scale, the narrow range above and below which muscle metabolic responses are drastically different suggests the existence of such a physiological "threshold" like the CP (Jones et al. 2010). As such, the Critical Power truly is a distinct and meaningful parameter, not simply an alternative to previously defined physiological thresholds (i.e. maximal lactate steady state, gas exchange threshold, etc.). Perhaps the most important study pushing this idea forward is the landmark study by (Poole et al. 1988b), which established that Critical Power demarcates the heavy and severe intensity domains. A fundamental feature of exercise in the severe domain is the development of a "slow component" that ultimately results in attainment of $\dot{V}O_{2peak}$ at (or close to) the point of exhaustion (Vanhatalo et al. 2007). Further, the power output that results in $\dot{V}O_{2peak}$ may be substantially below the power required for the attainment of $\dot{V}O_{2peak}$ during an incremental exercise test (Burnley and Jones 2018). The rate at which this slow component develops increases with the power demand above CP. Finally, support for the physiological existence of CP is seen in the distinct pulmonary gas exchange and blood acid-base profiles of exercise performed above and below the CP (Figure 5).

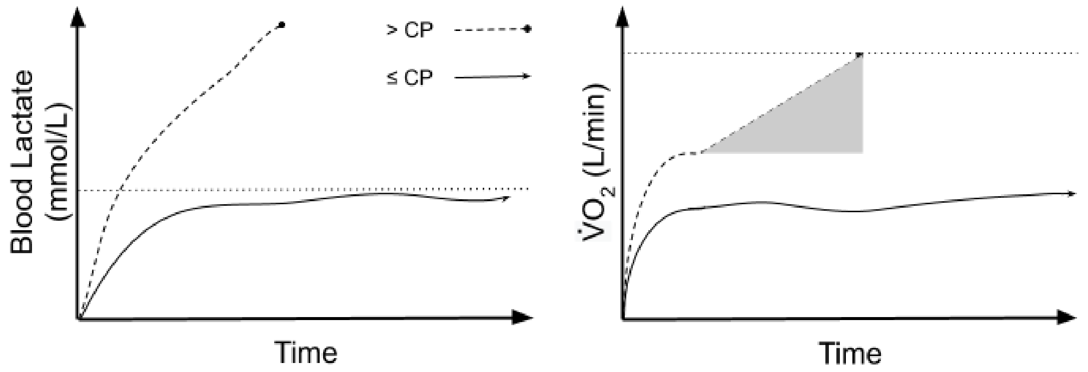


Figure 5. Representative blood lactate and V̇O₂ responses to constant exercise below (solid line) and above (dashed line) the CP. On the left, blood lactate quickly rises, but is stabilized around approximately 4mmoL (dotted line). When performing exercise above CP, blood lactate cannot be stabilized and continues to rise until exercise is stopped. On the right, V̇O2 quickly rises, then stabilizes for exercise below CP. During exercise above CP, the "slow component" of V̇O2 (shaded triangle) results in the attainment of V̇O2peak (dotted line) at the point of failure (filled circle).

Since then, the critical power has also been shown to separate additional physiological responses to exercise above/below CP, including distribution of cardiac output (Copp et al. 2010) and other indices of muscle metabolism, whether tested invasively via biopsy (Vanhatalo et al. 2016; Black et al. 2017) or non-invasively through 31P-Magnetic Resonance Spectroscopy (Jones et al. 2008). Additional markers of the fatiguing process are observed when exercise is performed above the CP, such as a lower intramuscular pH and creatine phosphate (PCr) (Wilson et al. 1988; Hultman et al. 1991; Karatzaferi et al. 2001; Jones et al. 2008). Furthermore, the degree of these muscular metabolic disturbances (pH, [La$^-$], [PCr], [Pi], etc.) are similar at the point of exhaustion for all power outputs in the severe domain regardless of the limit time. However, the severity of these metabolic disturbances is not observed in exercise below the CP, suggesting maintenance of metabolic steady state. Finally, the pulmonary gas exchange/ventilation (Poole et al. 1988a; Murgatroyd et al. 2014), metabolic (Jones et al. 2008; Poole et al. 2016; Black et al. 2017), blood acid-base (Poole et al. 1988b, 2016; Pringle and Jones 2002), cardiovascular (Copp et al. 2010), and neuromuscular (Burnley et al. 2012; Black et al. 2017) responses to exercise clearly demonstrate non-linear responses in exercise above the CP (for review, see Jones et al, 2019; Burnley & Jones, 2018).

2.1.2. W' Represents Exercise Tolerance in the Severe Domain

The "energetic reserve" originally reported by Monod and Scherrer represented a fixed amount of work that could be performed over the Critical Power. This was later renamed the anaerobic work capacity (AWC). However, the name was again changed to the curvature constant (W'), since the term AWC is a misleading oversimplification that all the energy is derived from anaerobic sources. This finite capacity for exercise is crucial to the CP model because it is used to determine the time to exhaustion for exercise performed in the severe domain, regardless of the work rate (Vanhatalo et al. 2011).

The actual limit of tolerance to exercise in the severe domain depends upon the interaction of three parameters: the anaerobic capacity, $\dot{V}O_{2peak}$, and the $\dot{V}O_2$ slow component, which is a progressive loss in muscular efficiency as severe exercise intensity increases (Burnley and Jones 2007). Therefore, the relative size of an athlete's W' is related to the size of the difference between the oxygen requirement at CP and $\dot{V}O_{2peak}$ (Vanhatalo et al. 2008, 2010), as well as the athlete's amount of non-oxidative energy stores (Miura et al. 1999, 2000). As such, it should be expected that endurance trained individuals will have a smaller W' relative to sprint trained individuals, since endurance trained individuals are able to exercise for extended periods of time at relatively higher percentages of their $\dot{V}O_{2peak}$ (Figure 6). This can be explained physiologically as a smaller amplitude of $\dot{V}O_2$ "slow component", since there is a narrow range between the $\dot{V}O_2$ at CP and $\dot{V}O_{2peak}$, and manifests in the CP model as a smaller W'.

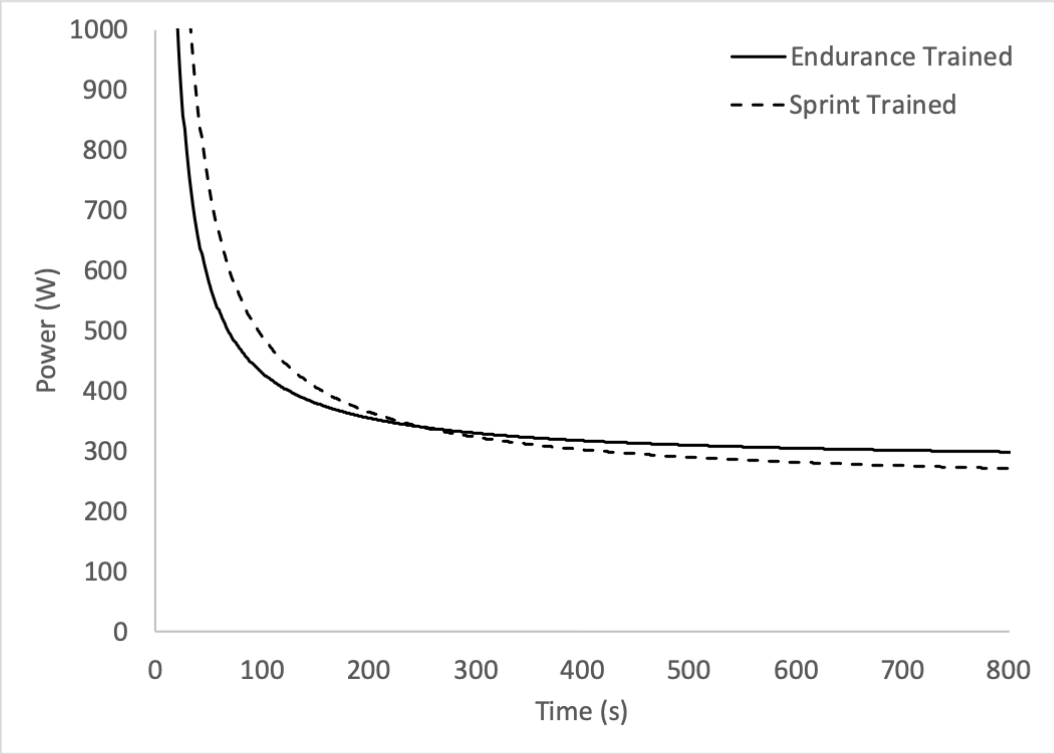


Figure 6. The parameters CP & W' reflect an athlete's capacity to perform across a broad range of time and are sensitive to the training of the athlete. For example, an endurance-trained athlete with a CP of 280 W and W' of 15 kJ is shown with the solid line. A sprint-trained athlete with a CP of 240 W and W' of 25 kJ is shown with the dashed line. As expected, the sprint-trained athlete is predicted to outperform the endurance-trained athlete at short durations (t < 250 s) but is outperformed at longer durations.

2.2. Significance of the CP/W' Concept

The CP model provides an objective, non-invasive assessment of an individual's aerobic and anaerobic potential. Unlike traditional methods that require expensive laboratory equipment or invasive blood samples, the testing protocol for CP only requires a measure of time and work performed. Further, the increasing popularity of portable power meters for bicycles also means that these tests can be completed by athletes using field data. Additionally, these parameters provide objective measures of adaptations following various interventions (nutritional/ergogenic, training interventions, & environmental, i.e. hypoxia).

2.2.1. Application to Sports & Exercise Science

Endurance training enhances pulmonary maximal oxygen uptake and the lactate threshold (LT; the intensity corresponding to the increase in blood lactate above resting levels), which are both strong determinants of endurance performance (Jones and Carter 2000). In sedentary populations, endurance training results in increases to both $\dot{V}O_{2peak}$ and LT (Bassett and Howley 2000). However, highly aerobic trained athletes most likely have a centrally limited $\dot{V}O_{2peak}$ and further adaptations will subsequently have a greater impact on LT than $\dot{V}O_{2peak}$ (Coyle et al. 1991). The CP is a superior indicator of cycling time trial performance, when compared to LT or $\dot{V}O_{2peak}$ (Smith et al. 1999). Therefore, the CP can be used to distinguish increases in performance capacity despite no increases in peak oxygen consumption or alternatively, to compare performance capacity of elite athletes who may have similar $\dot{V}O_{2peak}$ (Coyle et al. 1988).

The parameters CP and W’ can quantify changes in an athlete’s exercise tolerance following various training interventions. For example, CP has been reported to increase after short term continuous endurance training (Quigley and Jenkins 1992) and high intensity interval training (Gaesser and Wilson 1988; Poole et al. 1990; Vanhatalo et al. 2008). The W’ is negatively affected by glycogen depletion (Miura et al. 2000) and prior high-intensity exercise (> CP) (Heubert et al. 2005; Ferguson et al. 2007; Vanhatalo and Jones 2009), but has been shown to increase following sprint training (Jenkins and Quigley 1993). Due to the complex, interrelated physiological basis of CP & W’, interventions that affect one parameter may also affect the other (positively or negatively; Figure 7).

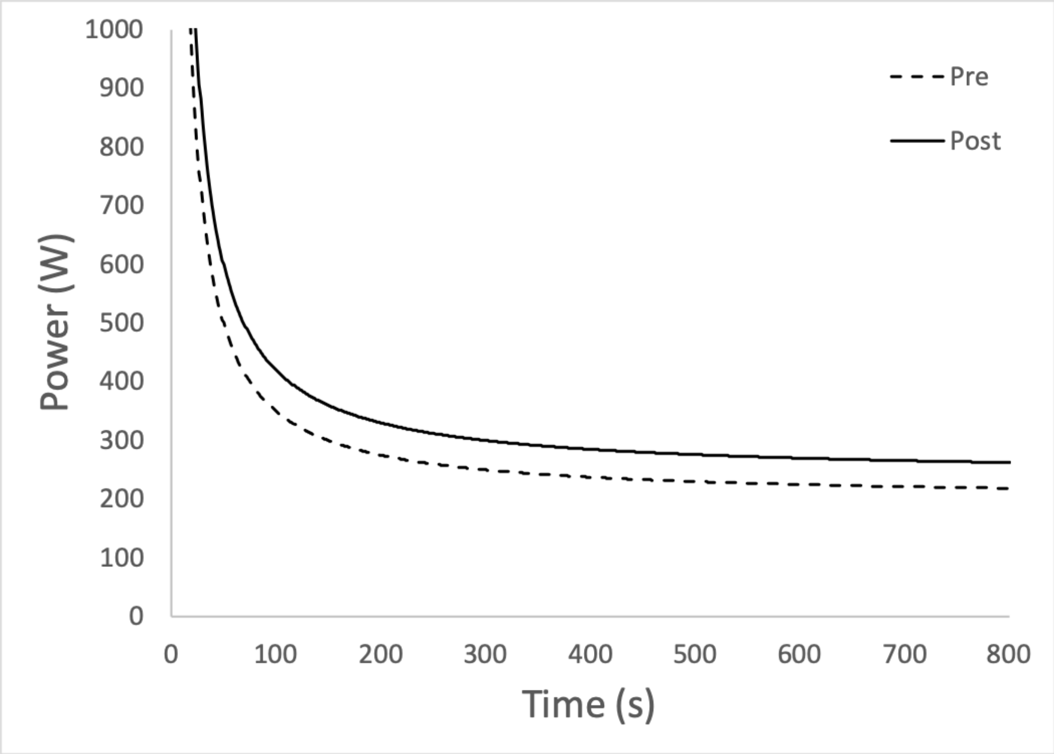


Figure 7. The CP/W' model can be used to show objective improvements in fitness following a training intervention. The dashed curve represents an athlete's fitness prior to the training intervention, and the solid trace represents the upward shift in sustainable power output following the training intervention. The upward shift in performance can be caused by an increase in CP, W', or both.

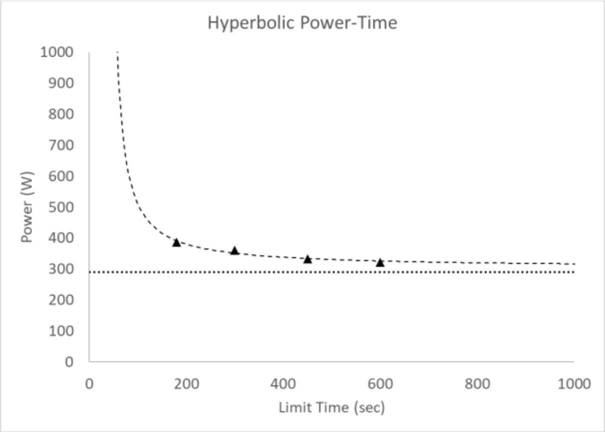
The CP model can also be used for optimizing workout prescription and pacing strategies in races. Provided the athlete's CP and W' are known, the time to exhaustion at any power output in the severe exercise domain can be calculated (Equation 2, shown below). For example, for an athlete with a CP of 300 W and a W' of 18.5 kJ, we can calculate the limit of tolerance at a power of 350 W, where t_{lim} = (18,500 J) / (350 W – 300 W) = 370 s. Conversely, it is also possible to compute the highest sustainable power output for a given duration of time (Equation 4, shown below). Using the same athlete as above, we can compute the highest sustainable power for 3.5 minutes (210 s) as P = (18,500 J / 210 s) + 300 W = 388 W. This has tremendous potential for optimizing race strategy for events that take place in the severe domain, or prescription of high intensity interval targets.

2.3. Parameter Estimation

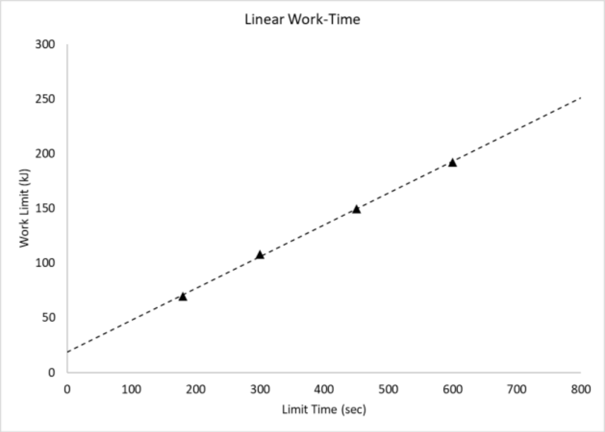
Obtaining the parameters of the CP model is rather simple, since it requires only a measure of work performed (i.e. cycling power meter, distance run, etc.) and a measure of time. Participants must complete several high intensity tests where they are tasked with maintaining a fixed external work rate for as long as possible. The precise time to the limit of tolerance for each high intensity test is secondary to ensuring that a maximal effort is performed (Jones et al. 2019). During these exercise tests, participants are expected to reach > 95% $\dot{V}O_{2peak}$. The key considerations for these high intensity tests have been outlined below:

- Number of trials needed: between 3-7 trials (Hughson et al. 1984; Gaesser and Wilson 1988; Poole et al. 1990; Bull et al. 2000; Smith and Jones 2001; Brickley et al. 2002; Pringle and Jones 2002; Dekerle et al. 2005; Vanhatalo et al. 2007; Black et al. 2015)
- Total difference between shortest and longest test should be at least 5 min (Hill et al. 2002; Vanhatalo et al. 2016)
    - Shortest test duration: no less than 2 min
    - Longest test duration: no more than 15 min
- Cadence should be consistent across trials (Jones et al. 2019)

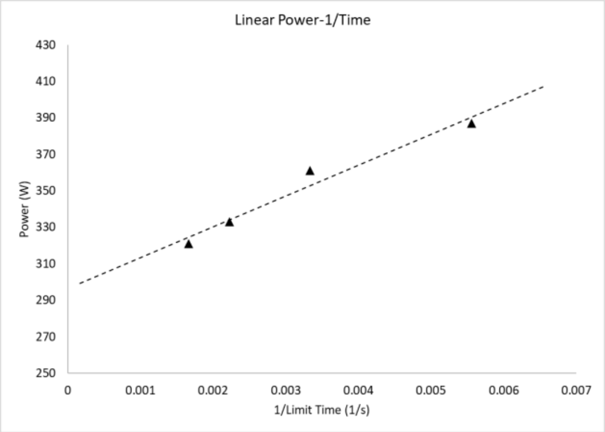
Once the traditional high intensity tests have been completed, the raw data can be plotted and the Critical Power can be calculated by fitting three different regressions/models to the prediction trial data: hyperbolic power-time (equation 2), linear work-time (equation 3), and linear power-time^{-1} (equation 4) (Hill 1993; Morton 2006; Jones et al. 2010). An example of the four prediction trials, fitted to the three different models is displayed below:



$$t_{lim} = \frac{W'}{P-CP} \tag{2}$$



$$Work_{lim} = W' + CP \cdot t_{lim} \tag{3}$$



$$P = CP + W' \cdot \left(\frac{1}{t_{lim}}\right) \tag{4}$$

The power (*P*) of each high intensity exercise test is defined as the mean power output measured across the duration of the exercise test. The limit of tolerance (t_{LIM}) is traditionally defined as the time from onset of the test to the moment at which cadence drops > 10 rpm for 5 sec, despite strong verbal encouragement. Since each model uses a different regression, each will result in slightly different values for CP/W', along with their standard error of estimate (SEE) from the regression. The SEE's for each regression parameter are expressed as coefficients of variation (CV%; i.e., relative to the parameter estimate). The "total error" associated with the modelling of the power-duration parameters is defined as the sum of the CV% associated with the CP and the CV% associated with the W'. The sum of the CV% is optimized for an athlete by selecting the model with the smallest total error to produce the "best individual fit" parameter estimates (Black et al. 2015, 2017). Below, the example of computing CP and W' from four high intensity exercise tests will be demonstrated using the three models:

Limit of Tolerance (s)	Limit of Tolerance^{-1} (s^{-1})	Mean Power (W)	Work Limit (kJ)
180	0.005555556	387	69.66
300	0.003333333	361	108.3
450	0.002222222	333	149.85
600	0.001666667	321	192.6

Table 1. Representative data from four constant power tests to exhaustion, used to determine CP & W'.

Model	CP (W)	CP S.E.E. (W)	CV (%)	W’ (kJ)	W’ S.E.E. (kJ)	CV (%)	Total Error CV (%)
Linear Work-Time	297	13	4.37	15.892	5.027	31.63	36.00
Linear Power-Time	308	15	4.87	12.640	2.915	23.06	27.93
Hyperbolic Power-Time	308	15	4.87	12.640	2.915	23.06	27.93

Table 2. Results of the three different two-parameter CP models. Note that although all three models use the same data, different estimates of CP & W’ are possible.

From the example above, it is evident that even when all prediction trials are performed in the recommended range of 2 - 15 min, small differences will be observed when a low number of trials are performed (i.e. 3-4 trials) (Triska et al. 2018). These differences in the estimation of the CP & W’ parameters using different models does not undermine the power-time relationship, but simply emphasizes the importance of minimizing measurement error, as outlined above (Jones et al. 2019). Along with reporting the derived values for CP and W’, the SE should also be reported. An additional test is recommended if the standard error (SE) for CP is > 5% or > 10% for W’ (Jones et al. 2019).

2.3.1. Physiological Bases of CP/W’

The relationship between power output and the limit of tolerance is the combined result of the bioenergetic properties of aerobic and anaerobic metabolism. Aerobic metabolism, although virtually unlimited in capacity, is rate limited by oxidative metabolism at the Critical Power. On the other hand, anaerobic metabolism is finite in capacity, but is theoretically rate unlimited. In practice, the work rate is limited by the force-velocity characteristics of the engaged muscle groups, with the upper limit being equal to the athlete's maximum cycling power.

Since they seem to identify the same theoretical threshold, or transition from aerobic to anaerobic metabolism, researchers have sought to compare the intensity of the Critical Power to other measures of the so-called "anaerobic threshold", including the Maximal Lactate Steady State (MLSS), and the respiratory compensation point, also known as the second ventilatory threshold (VT2). Most often, CP and VT2 are statistically higher than the MLSS; when compared to the MLSS, the CP is reported to be anywhere from 1-16% higher, with an average around 7% [e.g., 4% (Smith and Jones 2001), 9% (Pringle and Jones 2002), 16% (Dekerle et al. 2003), 5% (Dekerle et al. 2005), 9% (Mattioni Maturana et al. 2016), 1% (Keir et al. 2015)]. This discrepancy has caused debate to as whether the CP overestimates the maximal metabolic steady state or conversely, that MLSS underestimates the highest sustainable workload (Jones et al. 2019).

Some have argued that the maximal lactate steady state (MLSS) is a better measure of the maximal metabolic rate, since the MLSS has been shown to correlate with the "Functional Threshold" power, or power that be sustained for approximately 60 min (Gavin et al. 2012; Morgan et al. 2019). Not only is the duration of 60 min completely arbitrary, it also has no physiological basis. Instead, the gold standard of maximal metabolic rate should identify the maximum work intensity that separates distinct physiological domains (i.e. heavy v. severe), regardless of the time to exhaustion at that work rate.

This idea of separating distinct physiological responses is a theoretical and mathematical principle of the CP concept and has also been confirmed experimentally. Exercise performed 10 W above MLSS resulted in steady state $\dot{V}O_2$, suggesting that MLSS was not in the severe domain

(Mattioni Maturana et al. 2016; Iannetta et al. 2018). Furthermore, exercise above the CP results in attainment of $\dot{V}O_{2peak}$, provided the exercise is sustained sufficiently long enough for it to be reached. (i.e. > 2 min).

2.3.2. Assumptions of the CP/W' Model

The parameters CP and W' constitute a two-component, supply-and-demand bioenergetic system that is ideal for mathematical modeling. The supply of CP and W' are unique to an athlete (genetics, training, nutrition, etc.), while the demand component can be determined via a measure of external work rate (cycling power, running speed, etc.). Like any model, the Critical Power model has several assumptions that need to be acknowledged. In addition to the assumptions, a discussion about their validity is included. The first three assumptions are sufficient to derive the mathematical equations presented so far (Equations 2-4). However, it is important to realize that, in theory, there are several additional assumptions embedded within the first three assumptions.

1. There are only two components to the energy supply system for human exercise, termed aerobic and anaerobic. While it may be true that there are only two biochemical pathways, there are certainly more than two components to the energy source. This concept has been covered extensively by the bioenergetic hydraulic models proposed by Morton and Margaria (Margaria 1976; Morton 1985). For instance, aerobic energy is supplied by both aerobic glycolysis and oxidation of fatty acids. The anaerobic energy is comprised of both lactate-producing anaerobic glycolysis and alactic high energy phosphate compounds (PCr, ATP, ADP, etc)(Morton 1986).

2. The aerobic supply is unlimited in capacity but is rate limited. This limiting parameter is the critical power, CP. It is abundantly clear that the human body does not contain an unlimited energy supply. However, the aerobic source of energy (muscle free fatty acids, blood glucose, etc.) is relatively large compared to other available energy sources by orders of magnitude or more. However, it has been well established that the aerobic supply is truly rate limited through the development of measures such as CP, MLSS, CP, etc.

3. Conversely, the anaerobic supply is not rate limited but is capacity limited by the parameter W'. Like the aerobic energy supply, the anaerobic system requires specific biochemical substrates (muscle glycogen, blood glucose), which are clearly limited in capacity. Because the available concentration of blood glucose is relatively low and the rate of glucose liberation from glycogen is low, it is possible to expend the available glucose within the cell in a short period of time. Further, although top-end muscular power can be relatively large, it is certainly not unlimited. Thus, some upper rate limit *must* exist. For example, if the resistance of the cranks of a cycle ergometer is too high, the pedals cannot be turned, and no work is performed. Therefore, the idea of a time to exhaustion at points above CP is valid.

4. Exhaustion, and by implication termination of exercise, occurs when all W' has been utilized. The validity of this assumption is open to debate. Although a mechanical engine cannot function if its fuel source is empty, the human body appears to be noticeably different. Even at exhaustion, significant amounts of muscle glycogen and free fatty acids remain. Therefore, although it makes sense to assert that the W' is a fixed and limited value, the useable amount clearly is not. It would be unreasonable for muscle glycogen stores to be depleted in just a few short minutes of high intensity exercise. In fact, muscle glycogen is reduced only ~50% after 2 hours of heavy intensity cycling (Clark et al. 2019). Furthermore, since W' is known to be supplied by both aerobic and anaerobic energy metabolism, W' cannot be fully expended (i.e. even at the limit of tolerance, W’≠ 0), meaning that expending all of W’ does not necessarily explain the termination of exercise.

Additionally, it has been suggested that the higher the power requirement at the limit of tolerance, the more unused capacity remains (Saltin and Karlsson 1971). That is, the ability of the muscle to generate force could potentially limit exercise tolerance, not the size of W’, per se. This would imply that if the power requirement at the limit of tolerance were to be reduced, exercise could possibly continue, even at work rates exceeding CP. This notion is consistent with the idea of the threshold of local exhaustion proposed by Monod and Scherrer which “is reached when the muscle [group] cannot maintain the originally imposed work rate” (Monod and Scherrer 1965). Even upon reaching failure, an athlete’s entire anaerobic capacity might not be expended; rather, they are limited by the ability of the muscle to perform work. Consequently, any estimates of W’ based on the existing CP model assumptions will be underestimated, since the testing procedures are ended upon reaching the limit of tolerance at a given external work rate (i.e. the threshold of local exhaustion) (Morton 2006). This discussion will be expanded below (Section 2.4.1.).

Further, the role of psychology cannot be overlooked. Maximal voluntary cycling power measured after an exhaustive cycling exercise test showed that participants could still reach in excess of three times the required power output at exhaustion, suggesting a potential role of effort perception in limiting exercise tolerance during intense exercise (Marcora and Staiano 2010)

5. Aerobic power is available at its limiting rate CP the moment the exercise begins and remains so right up until the end of the exercise. It is well known that the establishment of oxygen uptake at *any* power output is *not* instantaneous, regardless of whether the kinetics of oxygen uptake follows a mono- or bi-exponential trajectory (Barstow and Mole 1991; Burnley and Jones 2007). Several minutes may be required, which may mean that the capacity of W’ is larger than the model predicts.

6. The power domain over which the model applies is all of $CP < P < \infty$*.* As mentioned in point 3, human muscle is clearly not all-powerful. As such, a finite upper limit to the available power must exist. This upper limit could be denoted as the maximum power (P_{max}).

7. The time domain over which the model applies is all $0 < t < \infty$*, and endurance at CP is infinitely long**.*** The idea of an infinite endurance is of a mathematical and theoretical origin more than physiological or functional, since there are plenty of non-bioenergetic reasons for cessation of exercise, such as boredom, central fatigue, or the need to eat or drink (Morton 2006). This means that the upper limit to the time domain is rather imprecise. Similarly, supramaximal efforts at very high powers (near P_{max}) are not captured well by the model either, but this is more due to the technical limitations in overcoming inertia and acceleration at high power outputs. From a theoretical perspective, time to exhaustion at P_{max} should be zero.

8. The efficiency of transformation of metabolic energy to mechanical energy is constant across the whole power (and time) domain(s). The gross efficiency for cycling is typically reported around 20% (Ettema and Lorås 2009). However, the gross efficiency during bouts of high intensity exercise is typically much lower, around 15% (Koning et al. 2013), and gross efficiency decreases over prolonged exercise due to increased oxygen cost (i.e. the $\dot{V}O2$ slow component) (Hopker et al. 2017). Further studies are required to assess the validity of this assumption.

9. CP and W' are constants, independent of P (and/or of t). As will be covered below, CP and W' are clearly responsive to changes in exercise habits. Additionally, the actual parameters are suspect to biological variations in genetics, diet, etc. Additionally, using different durations of high-intensity tests can result in marginally differing values for CP and W'.

2.4. Outstanding Issues with CP/W'

So far, this review has covered how the Critical Power is determined, what it represents, and how it can be applied to exercise and sports science. Despite the numerous beneficial features and uses of the Critical Power model, there remains one issue. Despite the theoretical definition of a indefinitely sustainable work rate, exercise at CP can typically not be sustained beyond 30 min (Quigley and Jenkins 1992; Brickley et al. 2002). This suggests that the CP using traditional testing methods may overestimate the metabolic steady state (Brickley et al. 2002). Thus, Monod and Scherrer made an error in reporting that "when the dynamic work is inferior or equal to the critical power…exhaustion cannot occur". Mathematically, their argument is correct, since $t_{lim} = W' / (CP - CP)$ reduces to $t_{lim} = W'/0$. However, this is clearly not the case.

2.4.1. Muscular Failure Does Not Equal Exhaustion

The conserved hyperbolic power-duration (or velocity-duration) relationship across muscle groups suggests a common underlying mechanism for task failure. However, the current power-duration model is merely an empirical and integrated model of performance and that it cannot explain the termination of exercise. In fact, intense debate exists around the proximal cause of task failure during high-intensity exercise, as was considered in the discussion to assumption 4 above. The three main proposed causes are: 1) attainment of sensory tolerance limit, 2) central regulation by a brain-centered governor preventing severe metabolic disturbances, and 3) effort-based decision to disengage from task. A further discussion is beyond the scope of this literature review, but it is important to highlight that the CP model does not explain task failure and that it cannot predict physiological processes during exercise. Rather, it allows for reasonable estimate of the limit of tolerance for any power output in the severe exercise domain.

In their original work, Monod & Scherrer presented the concept of a *Threshold of Local Exhaustion*, which is reached “when the muscle [group] cannot maintain the originally imposed work rate” (Monod and Scherrer 1965). This suggests that even upon reaching failure in the existing CP/W’ testing protocols, some capacity to perform work remains beyond that point, but that capacity is *rate-limited*. This idea was also reported in 1971 by Saltin & Karlsson who stated that “the higher the power requirement at exhaustion, the more it is that remains” (Saltin and Karlsson 1971), a reference to some residual energetic capacity remaining at exhaustion. For example, when an athlete reaches fatigue at a high work rate, they are going to be rate-limited by muscle dynamics, not by the capacity of W’. It is intuitive that an inverse relationship exists between the power demanded at the point of exhaustion and the size of the residual remaining, i.e. when task failure is reached at a high intensity, a larger residual capacity remains (Figure 8).

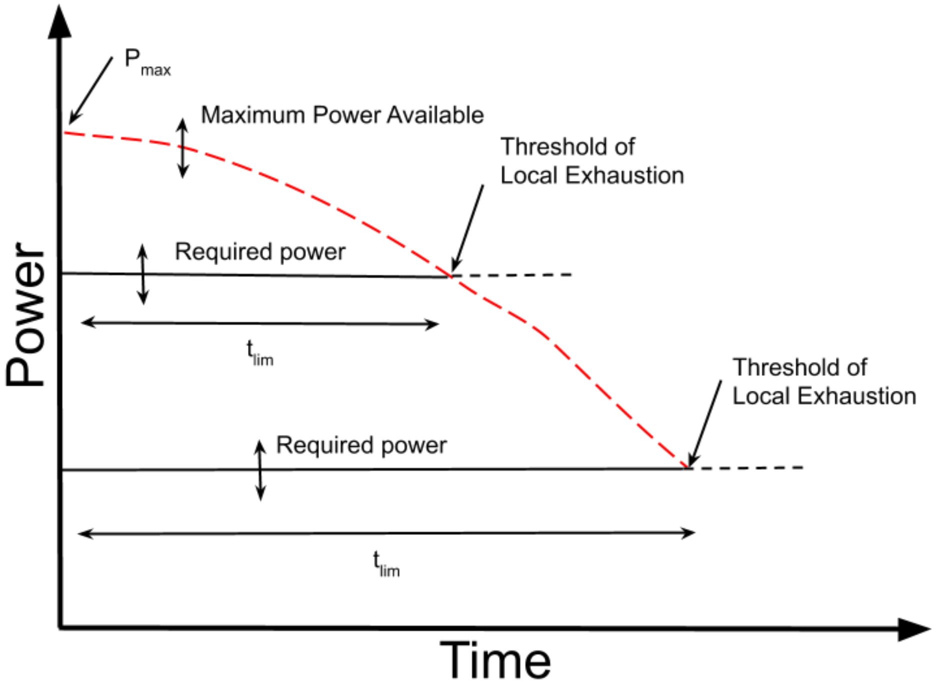


Figure 8. The limit of tolerance is determined by the relationship between the required power output and an athlete's W'. It could be presumed that some maximal power available (red dashed line) begins at a participant's maximal instantaneous power (P_{max}) at the onset of exercise and declines during constant work above CP as W' is expended, until it reaches the required work rate (the solid black lines), at which point the threshold of local exhaustion is reached. It could be inferred that the maximum power available is equal to the maximal work rate at that moment. Since the limit of tolerance is reached sooner at the higher intensity trial, a larger range of power is available between the point of failure and the CP, meaning that a larger residual capacity is expected at higher intensity trials.

However, the current testing protocols call for termination of the test when the participants' cadence decreases, suggesting they are at the limit of tolerance. As such, the current testing protocols cannot explain the full ability of an athlete to perform work above the Critical Power. Rather, the work rate should be gradually reduced as the limit of tolerance is reached. This will allow athletes to express their *full* capacity for exercise above the Critical Power.

To our knowledge, this study is the first attempt at capturing and quantifying the residual capacity that remains upon reaching exhaustion, alluded to by Monod & Scherrer and Saltin & Karlsson. In principle, the time until the threshold of local exhaustion is reached depends on the interaction between the external force required, the maximum force that the muscles can produce, and the endurance of the muscle cells. The existing protocols have not yet been optimized to capture the capacity of the athlete to perform once the initial limit of tolerance is reached, since the high intensity exercise-test is terminated at the threshold of local exhaustion, rather than at *total* exhaustion. Because of this, the existing model will underestimate an individual's capacity to perform high-intensity exercise. By underestimating an athlete's capacity above threshold, the calculated CP is positively biased due to the mathematical relationship between these two parameters (Figure 9).

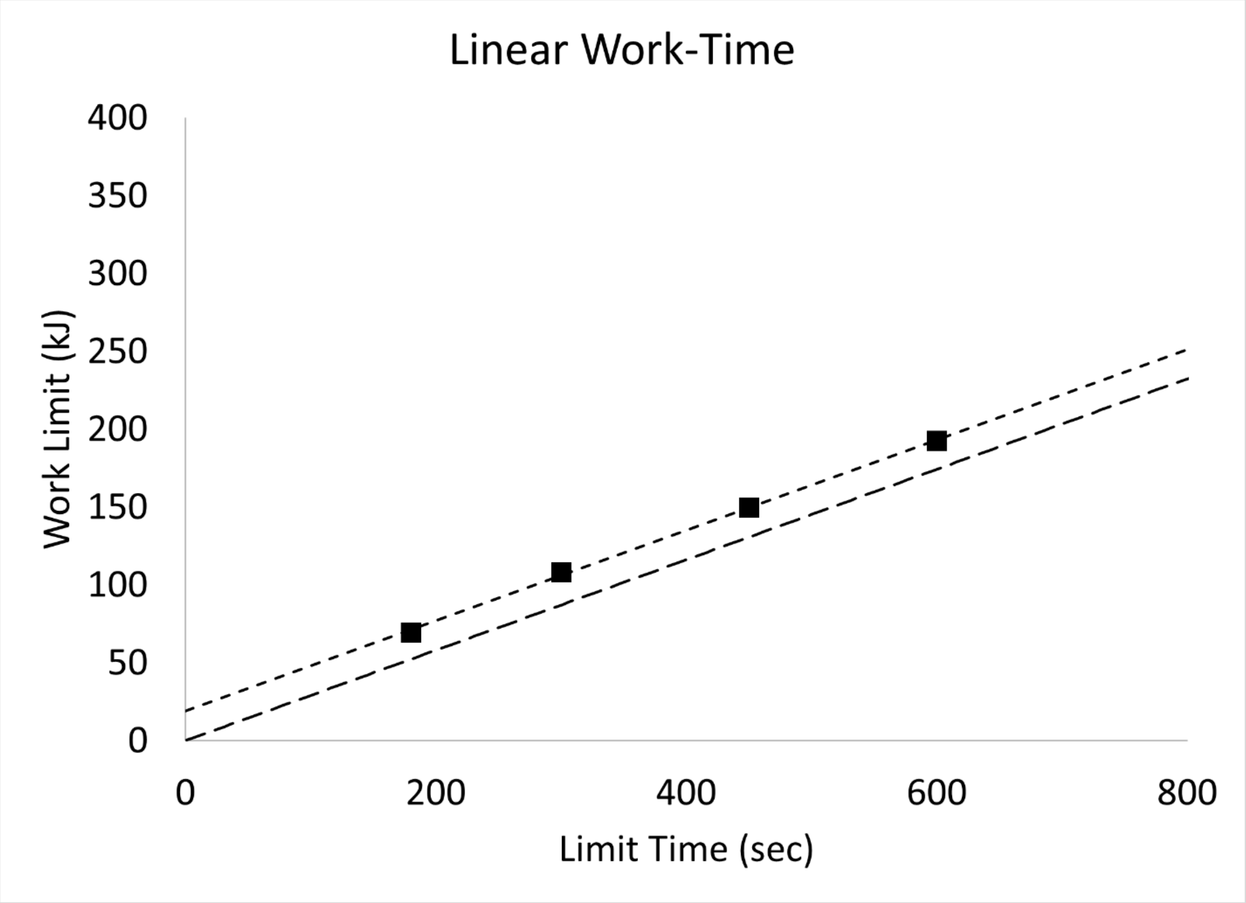


Figure 9. In theory, the lower dashed line is the boundary of work that can be performed indefinitely (without accumulation of peripheral fatigue), according to assumption 8. The literature suggests that this work rate may be overestimated using the current testing protocols. Therefore, by accounting for additional W' the difference between the maximal work rate (upper dashed line) and the Critical Power (lower dashed line) will be increased, leading to a lower, more sustainable work rate for Critical Power.

3. Objectives and Hypotheses

3.1. Objectives

The objectives of this study are to:

1) Test for a residual capacity at the limit of tolerance.
2) If a residual capacity does exist, test for the influence of this capacity on the calculation of the Critical Power.

3.2. Hypotheses

The hypotheses of this study are:

1) A clinically significant residual W' capacity does exist.
2) The size of W'_{RES} observed in each trial is inversely related to t_{LIM} used in the testing protocols.
3) Accounting for W'_{RES} will result in an improved calculation of the CP, as determined by a significantly lengthened time to exhaustion at CP.

3.2.1. Expected Results

Due to the mathematical relationship between CP & W', increasing the W' will result in a lower Critical Power. Both CP and W' contribute to the amount of work performed over time (Equation 2). Thus, when a fixed amount of work is performed and the size of the W' is increased, the CP must decrease.

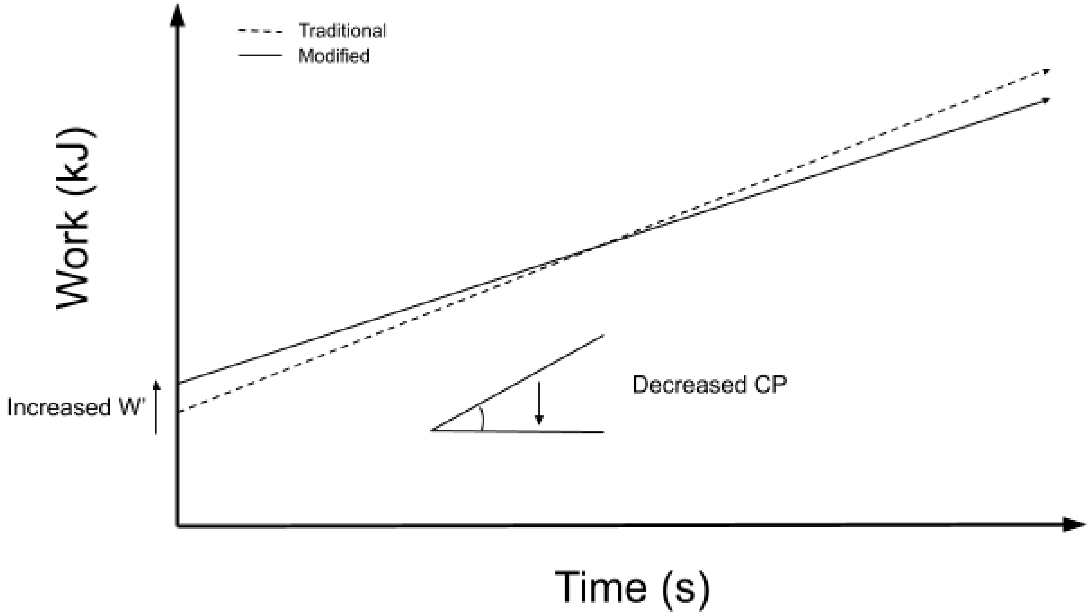


Figure 10. Expected results. By accounting for a larger W' (increased y-intercept), the slope must decrease (meaning a lower Critical Power).

4. Methods

4.1. Participants

All participants were informed of the experimental protocol and the associated risks prior to participating in the experiment. Verbal and written consent was obtained from each participant. The study was approved by the Bioscience Research Ethics Board of Brock University (Brock REB 19-062) and conformed to the standards set by the Declaration of Helsinki.

In total, 17 participants were recruited for the study; 9 participants were able to complete the full study protocol preceding the COVID-19 lockdown. Participants were healthy, well-trained male and female cyclists or triathletes (aged 18-55), classified as performance level 3 or higher (on a scale of 1-5) on the basis of De Pauw et al. 2013. Participants were competitive racers or riders who were familiar with maximal efforts such as hard interval efforts, time trials, or racing.

Variable	Mean ± SD (*n*=9)
Age (y)	33.4 ± 13.1
Height (cm)	177.2 ± 8.4
Weight (kg)	73.4 ± 10.3
Body Fat (%)	12.7 ± 4.1
HR_{max} (bpm)	187 ± 16
$\dot{V}O_{2peak}$ (mL· kg $^{-1}$· min $^{-1}$)	51.56 ± 8.95
$\dot{V}O_{2peak}$ (L · min $^{-1}$)	3.74 ± 0.66
Maximum Power Output (W · kg $^{-1}$)	5.19 ± 0.69
Maximum Power Output (W)	378 ± 56

Table 3. Participant characteristics. All data presented as Mean ± SD.

4.2.Experimental Design

All participants completed a familiarization session and 6 experimental sessions (Figure 11). Participants were provided a minimum of 24 h rest between sessions, and all testing was completed over the course of 5 weeks. Participants were instructed to maintain their normal training outside of the laboratory for the duration of the study, and to abstain from alcohol consumption 24 h prior to arriving at the laboratory. Additionally, participants were also asked to maintain their usual diet, and to arrive at the laboratory as if they were arriving for competition. Upon arrival to the laboratory, subjects provided a small urine sample and urine specific gravity (USG) was tested to ensure euhydration (1.000-1.020). If USG > 1.020, participants received 500 mL water to drink and were retested after 30 minutes, or the session was cancelled and rescheduled. Water was be provided *ad libitum* during all sessions in the laboratory.

On the first visit, participants performed a graded exercise test to failure and were familiarized with the high intensity protocol used for the study. On the following four visits, participants completed high intensity tests to exhaustion, in a randomized and counterbalanced order. These four tests were used to obtain values for CP & W' using the traditional method (CP_{TRAD}; W'_{TRAD}) and a novel, modified method (CP_{MOD}; W'_{MOD}). On the final two visits, participants performed tests to exhaustion at an intensity equaling the predicted 30 min power from the traditional CP model (30 MMP_{TRAD}) or the modified CP model (30 MMP_{MOD}), in a randomized order. For these final two sessions, participants were not provided any workload or performance feedback. Before all prediction tests and tests to exhaustion, participants were provided a 5 min standardized warmup at 100 W, a 5 min rest, and 3 min unloaded cycling (Vanhatalo et al. 2007).

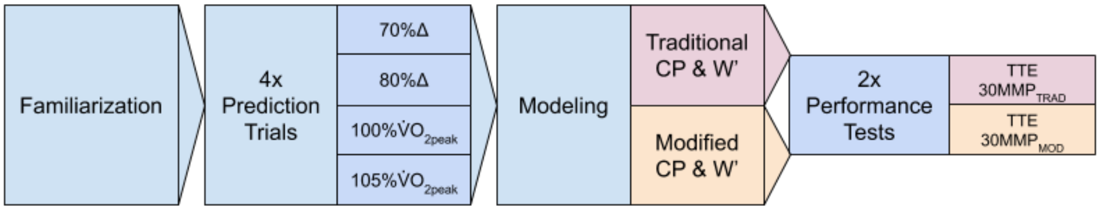


Figure 11. Experimental design.

4.2.1. Body Composition

During the first visit, participants provided their age (years), and height (cm) and weight (kg) were measured. To determine body density, skin fold thickness was measured at seven different sites all on the right side (triceps, sub-scapula, abdomen, supra-iliac crest, mid-axilla, thigh, and pectoralis major) (Jackson and Pollock 1978) and body fat was calculated using the Siri equation (Siri 1961).

4.2.2. Incremental Test & Familiarization

All tests were completed on the same cycle ergometer (Velotron; RacerMate, Seattle, WA, USA) controlled by the accompanying software (RacerMate One; RacerMate Inc., Seattle, USA). On the first visit to the laboratory, the ergometer seat and handlebars were adjusted to replicate each participant's natural riding position.

Peak oxygen uptake ($\dot{V}O_{2peak}$) and the gas exchange threshold (GET) were assessed in a thermoneutral environment (~22°C, ~30% relative humidity) on the cycle ergometer. Participants began the test with a standardized 5-minute warmup at 100 W, followed by 25 $W \cdot min^{-1}$ increase in workload until volitional exhaustion, or until cadence dropped by > 10 rpm for 5 s despite strong verbal encouragement. A soft, silicone facemask connected to an online gas collection system was worn throughout the test to collect expired gases and determine GET and $\dot{V}O_{2peak}$. GET has been used as an index of the anaerobic threshold, since it can be measured non-invasively by using the V-Slope method (Beaver et al. 1986). In short, GET is determined by finding the breakpoint of the carbon dioxide production ($\dot{V}CO_2$) and oxygen uptake ($\dot{V}O_2$) relationship. $\dot{V}O_{2peak}$ was defined as the highest 30s average $\dot{V}O_2$. Peak Power Output (PPO) was defined as the highest 1-minute average power during the incremental test.

GET and $\dot{V}O_{2peak}$ were used to determine and standardize the workloads for the following high-intensity tests. The work rates for the four high intensity prediction tests to determine CP & W' were equal to: 70%Δ (i.e. 70% of the difference between GET and $\dot{V}O_{2peak}$) as well as 80%Δ, 100% $\dot{V}O_{2peak}$ & 105% $\dot{V}O_{2peak}$, according to (Vanhatalo et al. 2007). The work rate for these tests were obtained from the linear relationship between power and $\dot{V}O_2$ recorded during the incremental test, and have been shown to avoid known constraints with mechanical power output ($t_{LIM} < 2$ min) and conflicting issues with central fatigue ($t_{LIM} > 15$ min) (Hill 1993; Morton 2006), as well as improving the resulting curve fit by covering a broad range of times (Hill 1993). Approximately thirty minutes following the incremental exercise test, participants were familiarized with the prediction trial test at the 100% $\dot{V}O_{2peak}$ intensity.

Following another thirty-minute break, participants completed a 30 s Wingate Anaerobic Test. The ergometer was controlled using accompanying software (Velotron Wingate Software; RacerMate, Inc, Seattle, WA, USA) and participants were instructed to remain seated for the entirety of the test. Strong verbal encouragement was provided throughout the test.

4.2.3. Prediction Trial Testing Protocol

To obtain the parameters of CP & W', each participant completed four high intensity tests to exhaustion. We chose a CP protocol using 4 prediction tests because time to exhaustion trials of various durations should be used to minimize the influence of shorter trials when modelling CP (Bishop et al. 1998). For each of these tests, participants were asked to sustain a predetermined power output as long as possible. The order in which these four tests were completed was randomized and counterbalanced for all participants.

Following a standardized 5-minute warmup at 100 W, participants were asked to ride against a fixed external resistance for as long as possible while maintaining a constant cadence. Participants were instructed to remain seated for the entirety of the test. To ensure an all-out effort, strong verbal encouragement was provided throughout the test and subjects were provided verbal & visual feedback to maintain a steady cadence throughout the test. Visual feedback was provided through a computer monitor placed approximately 1 m in front of the participant with a cadence gauge, which showed the target cadence ± 10 rpm. The participants were specifically tasked with maintaining a cadence as close to their initial self-selected target as possible (e.g., 95 rpm) rather than attempting to achieve or maintain a set effort by reducing cadence, and verbal feedback was provided any time participants deviated more than 2 rpm from target cadence. Participants were blinded to all other performance metrics (power, HR, time, etc.).

When cadence decreased 5 rpm below the target cadence or power was > 5 W below the target power, t_{LIM} was recorded. It is also expected that the participant had reached $\geq$ 95% $\dot{V}O_{2peak}$ obtained from their incremental ramp test. The main purpose of each test is to reach the point of exhaustion (t_{LIM}) rather than complete a predetermined amount of time. Participants were not informed when they had reached the limit of tolerance, and the prediction tests continued beyond t_{LIM}. However, upon reaching t_{LIM}, a researcher gradually reduced the workload and participants were instructed to hold their target cadence. The resistance was reduced continually, enabling the participants to maintain their target cadence. The test was concluded when participant power output approached approximately 80% of the starting target power or when participants had reached volitional exhaustion.

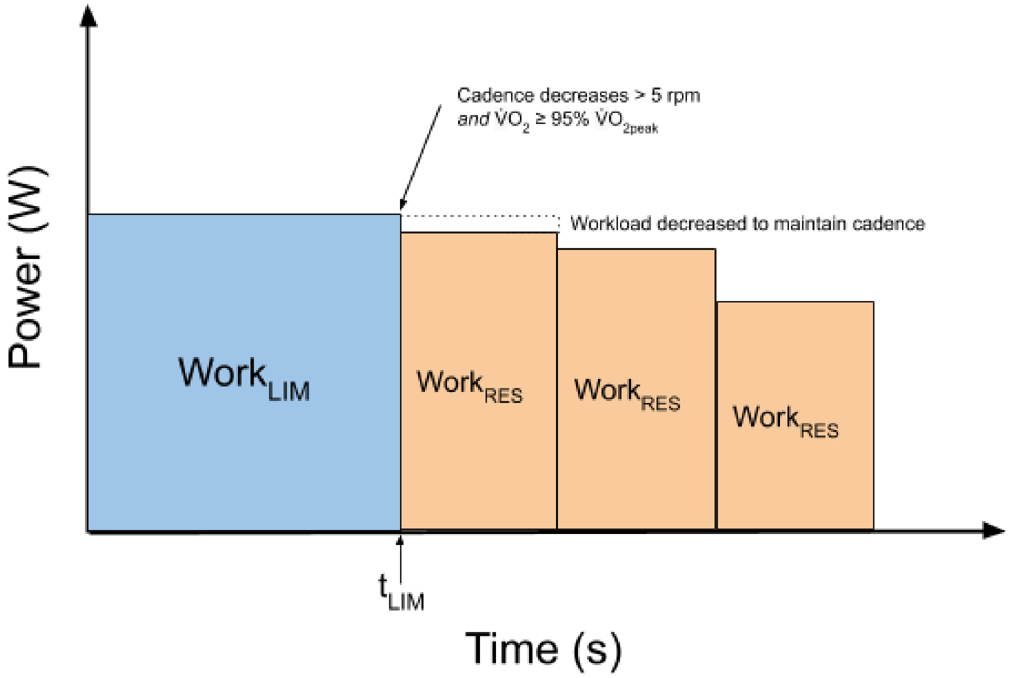


Figure 12. Representative prediction trial test. Notice that the external work rate is held constant until participant reaches >95% $\dot{V}O_{2peak}$ and cadence drops 5 rpm below self-selected target. At t_{LIM}, the external workload was reduced to maintain a constant cadence and participants were verbally encouraged to continue working. t_{END} could not be determined until all four trials had been completed and CP_{TRAD} was estimated.

The t_{LIM} obtained from the four prediction trials were used for calculating CP/W′ by plotting t_{LIM} against the work performed during the test, as traditionally done (Monod and Scherrer 1965; Moritani et al. 1981). The end of the test (t_{END}) for the modified protocol was determined following the conclusion of all four prediction trial tests and the calculation of CP_{TRAD}. t_{END} was determined using the last second of work performed above the traditionally calculated CP, or the point at which cadence dropped > 5 rpm below the target cadence for 5 seconds (Figure 13 below). The total work performed (in kJ) from $t = 0$ until $t = t_{LIM}$ during the high intensity tests is reported as the work limit ($Work_{LIM}$) and is represented as the blue shaded area in Figure 13.

The residual work (Work_{RES}) for each test is reported as the total work performed (kJ) from t = t_{LIM} to t = t_{END} and is represented as the sum of the orange shaded areas in Figure 13 below.

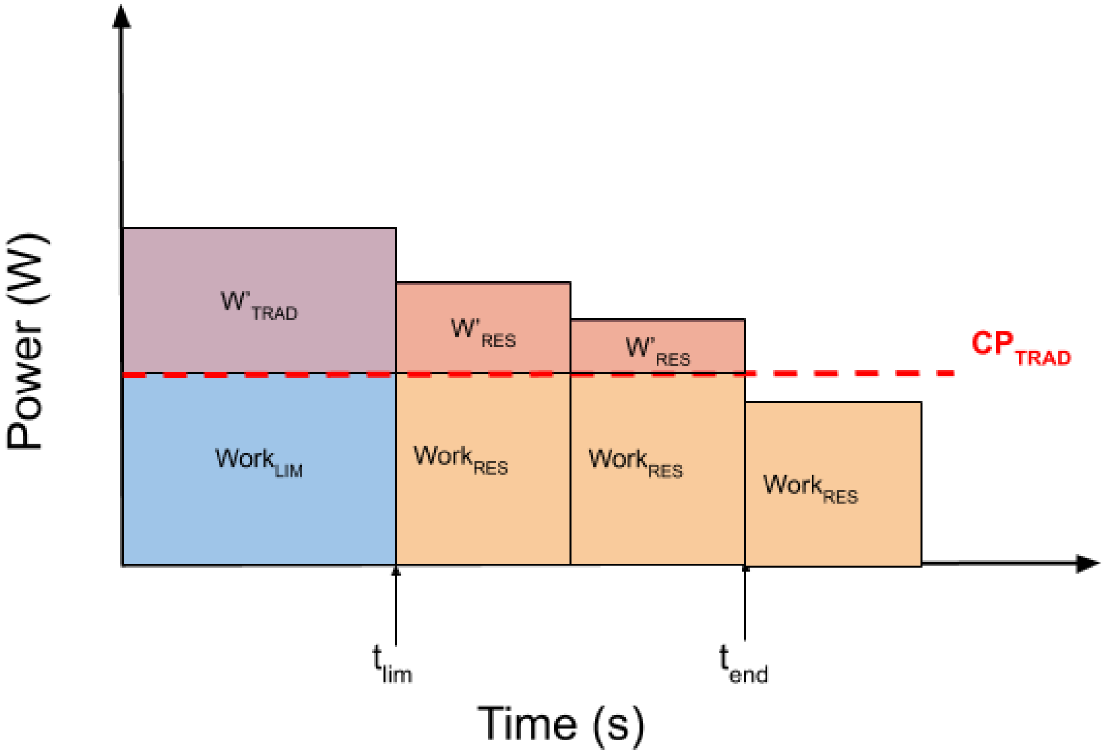


Figure 13. Representative calculation of W'$_{RES}$. The end of test was calculated as the last second at which work was performed above CP. The residual W' work was calculated as all work completed above CP between t_{LIM} and t_{END}, represented as the shaded red sections above. The limit work (Work_{LIM}) and residual work (Work_{RES}) were plotted against t_{END} to calculate CP_{MOD} and W'$_{MOD}$.

4.2.4. Curve Fitting

Linear regression was used to provide estimates of CP and W' from the results of these prediction tests, using the linear work–time model (Figure 3; Equation 1). The traditional linear work-time relationship was created for each participant by plotting Work_{LIM} from each trial against its respective t_{LIM} and a least squares linear regression was fitted to the data. The slope of the regression is equal to the CP (CP_{TRAD}) and the y-intercept is equal to the W' (W'$_{\text{TRAD}}$) (Monod and Scherrer 1965). Both parameters are reported with their standard errors. It was expected to see a standard error of the regression parameters of < 5% for CP and < 10% for W’, according to (Jones et al. 2019). We chose the 2-parameter model because the 3-parameter model requires measurement of maximal instantaneous power using special cycle ergometers or extrapolation by vertical jump on a force platform (Vinetti et al. 2019). Thus the 2-parameter model is the most used CP model in sports science and exercise physiology due to its simplicity and accuracy in performance predictions (Jones and Vanhatalo 2017).

To capture the influence of the residual work capacity on the calculation of a modified CP and W’ (CP_{MOD}; W'_{MOD}), the total work completed ($Work_{LIM}$) and residual work completed ($Work_{RES}$) were summated and plotted against the t_{END} for all four high intensity tests. CP_{MOD} and W'_{MOD} were extracted using the same linear work-time regression outlined above (Figure 3; Equation 1) and reported with their standard errors. W'_{RES} was calculated as the work performed (in Joules) *above* the traditional CP, from $t = t_{LIM}$ to $t = t_{END}$ (Figure 13).

4.2.5. Tests to Exhaustion

For the final two experimental trials, participants completed tests to exhaustion at an intensity equal to the predicted 30 min mean maximum power (MMP) from the traditional CP model (30 MMP_{TRAD}) or the modified CP model (30 MMP_{MOD}). These intensities were determined for each participant by extracting the CP and W’ for each model from the linear regression of the prediction trial data (see section 4.2.4 – Curve Fitting) and substituting those parameters into Equation 2.

The tests to exhaustion were concluded at the point at which a participant’s cadence decreased by > 10 rpm for 5 s. Power and cadence data were collected continuously during the test. Fingertip capillary blood samples were collected and analyzed for blood lactate concentration [La$^-$] immediately preceding the time trial, every 5 min during exercise, and at the conclusion of the test to exhaustion (Brickley et al. 2002; de Lucas et al. 2013). Rate of perceived exertion (RPE) was assessed using a 6-20 scale (Borg 1982) and recorded at the same time points as blood lactate. During time trials, participants will only receive visual feedback of cadence. No verbal encouragement was given during the TTE to eliminate the superimposition of any extraneous verbal statements (Blanchfield et al. 2014).

4.2.6. Equipment

All tests were completed on the same cycle ergometer (Velotron; RacerMate, Seattle, WA, USA). The cycle ergometer was controlled by the accompanying software (RacerMate One; RacerMate Inc., Seattle, USA) and recorded time, power output, and cadence every second.

During all four predictions trials, participants wore a silicone facemask (Hans-Rudolf, Carefusion, Germany). Pulmonary gas exchange was measured breath by breath, and bin-averaged over 10 s periods. The inspired and expired gas volume and gas concentration signals were sampled continuously at 100 Hz (ML206 Gas Analyzer, ADInstruments Inc. Colorado Springs, USA) via a capillary line connected to the mask. The analyzer was calibrated prior to each test with gases of known concentration and the turbine volume transducer was calibrated using a 3 L syringe (Hans Rudolf, MO). The volume and concentration signals were time-aligned by accounting for the delay in capillary gas transit and analyzer rise time relative to volume signal. Heart rate was determined continuously from the R-R intervals using a 3-lead electrocardiogram (Bio Amp; ADInstruments, Colorado Springs, USA).

Blood lactate concentration during the two tests to exhaustion was measured with a handheld device (YSI 23L Lactate Analyzer; YSI Scientific, Yellow Springs, USA) using a capillary blood sample obtained from the fingertip prior to the warmup, every 5 min during the test, and at the conclusion of the test.

4.2.7. Statistical Analysis

Data are presented as Mean ± SD, unless otherwise noted. A student's paired t-test was used to test for a statistical difference between the CP_{TRAD} and CP_{MOD}, as well as W'_{TRAD} and W'_{MOD}. To capture the relative magnitude of the difference, effect sizes are reported using Cohen's *d*. Small, medium, and large effect sizes are considered as $d \geq 0.2$, $d \geq 0.5$, and $d \geq 0.8$, respectively (Cohen 1998). Additionally, a bi-variate correlation analysis was used to test for the relationship between the size of the residual work capacity above threshold (W'_{RES}) and the limit of exhaustion (t_{LIM}). Normal distribution was assessed, and if the assumption of sphericity could not be met, the Greenhouse–Geisser correction was used. All continuous variables recorded during the prediction trials were analyzed using separate condition [70% Δ, 80%Δ, 100% $\dot{V}O_{2max}$, 105% $\dot{V}O_{2max}$] x Time [Baseline, t_{LIM}, t_{END}] repeated measures analysis of variance (RM-ANOVA). A Bonferroni *post hoc* analysis was used to test significant main effects. Paired sample *t*-tests were performed to test significant main effects at specific time points within-group effects.

To test the applied significance of the newly determined CP, a student's paired t-test was used to compare TTE at 30 MMP_{trad} vs. TTE at 30 MMP_{mod}. Effect size is also reported using Cohen's *d*, same as above. Physiological responses to exercise at 30 MMP (heart rate (bpm) and blood [La-] ($mmol \cdot L^{-1}$) were analyzed using a two-way Model [CP_{TRAD}, CP_{MOD}] x Time [Baseline, Exhaustion] RM-ANOVA. REP data was also compared between baseline and exhaustion. Ordinal data are presented as the median (quartiles 1 and 3). Statistical significance was set at $p < 0.05$. All analyses were performed using IBM SPSS Statistics for Windows (SPSS version 25; IBM Corp., Armonk, N.Y., USA).

5. Results

No significant difference in weight or hydration was observed for the duration of the study. All participants completed all testing inside a five-week window and no participants reported any illness for the duration of the study.

5.1. Incremental & Wingate Tests

The mean ramp-test $\dot{V}O_{2peak}$ was 3.77 ± 0.66 L · min^{-1}, maximum ramp-test power was 378 ± 53 W, and the GET was 2.53 ± 0.56 L · min^{-1}. The peak power, typically reached in the first 2 seconds of the Wingate test, was 1140 ± 251 W (~300% max ramp test power). The mean power over the 30 s Wingate test was 755 ± 108 W (~200% max ramp test power). The mean work performed in the Wingate was 22624 ± 3230 J. The fatigue index was 46.3 ± 11.1 %.

Maximum Power (W)	Maximum Power (W · kg^{-1})	Mean Power Output (W)	Mean Power Output (W · kg^{-1})	Minimum Power Output (W)	Minimum Power Output (W · kg^{-1})	Fatigue Index (%)
1140 ± 250	15.52 ± 2.32	755 ± 108	10.34 ± 1.17	539 ± 72	7.40 ± 1.08	46.3 ± 10.44

Table 4. Maximum, Mean, and Minimum power outputs (absolute and relative to weight) for the Wingate test. Fatigue Index was calculated as a percentage of the lowest 5 s power divided by the highest 5 s power. Data presented as Mean ± SD.

5.2. Prediction Trials

The work rates based upon various percentages of the GET and $\dot{V}O_{2peak}$ resulted in four distinct conditions, which avoided constraints with mechanical power output (< 2 min) and conflicting issues with central fatigue (an increasing factor for exercise lasting > 15 min). The limit of tolerance and power outputs for those four conditions are displayed as mean ± SD in the table below. There was a significant difference in t_{LIM} ($F_{[3,24]} = 85.456$, $p < .001$) between the four test conditions. Bonferroni *post hoc* tests indicated t_{LIM} was significantly shorter in the 70%Δ (534.6 ± 76 s) condition than the 80%Δ (435.7 ± 88.9 s), 100% $\dot{V}O_{2peak}$ (300.3 ± 87.6 s), and 105%$\dot{V}O_{2peak}$ conditions (205.7 ± 54.7 s; all $p < 0.05$). There was a significant difference in mean power output between test conditions ($F_{[3,24]} = 87.878$, $p < .001$). Follow up tests showed the 105% $\dot{V}O_{2peak}$ condition resulted in significantly higher power output than the 100% $\dot{V}O_{2peak}$, 80%Δ, and 70%Δ conditions (all $p < .05$). No statistical difference in mean power output was observed between 70%Δ (308.7 ± 50.1 W) and 80%Δ (317.7 ± 48.2 W; $p > .05$).

As a whole, these data provided a sufficiently wide range of maximal efforts to failure across the time domain and resulted in parameter SEE's that were in the recommended range (< 5% for CP, <10% for W').

	70% Δ	**80% Δ**	**100% $\dot{V}O_{2peak}$**	**105% $\dot{V}O_{2peak}$**
t_{LIM} (s)	534 ± 25	436 ± 30	300 ± 30	205 ± 18
Power (W)	308 ± 17	318 ± 16	337 ± 17	350 ± 18
W'_{res}	329 ± 118	381 ± 78	1142 ± 451	1151 ± 359

Table 5. The limit of tolerance and mean power output for the four conditions. Upon reaching the limit of tolerance, the work performed above CP from t_{LIM} to t_{END} were calculated as the W'_{res}. Data presented as Mean ± SEM.

5.2.1. Prediction Trials - Physiological data

There was a significant main effect for time on HR ($F_{[1.002, 8.013]} = 164.99$, $p < .0001$). Follow up tests showed a significant difference between HR at baseline (116 ± 5 bpm) and t_{LIM} (179 ± 5 bpm), as well as between baseline and t_{END} (178 ± 5 bpm). There was no main effect for condition on HR, nor was there a significant interaction between time and condition (all $p > .05$).

There was a significant main effect for time on $\dot{V}O_2$ ($F_{[1.02, 7.14]} = 200.69$, $p < .0001$). *Post hoc* testing showed a significant difference between $\dot{V}O_2$ at baseline (1.53 ± 0.04 $L \cdot min^{-1}$) and

t_{LIM} (3.69 ± 0.17 L · min^{-1}), as well as between baseline and t_{END} (3.63 ± 0.17 L · min^{-1}). There was no main effect for condition on $\dot{V}O_2$, nor was there a significant interaction between time and condition (all $p > .05$).

There was a significant main effect for time on $\dot{V}CO_2$ ($F_{[1.084,\ 7.587]} = 334.64$, $p < .0001$). *Post hoc* testing showed a significant difference between $\dot{V}CO_2$ at baseline (1.39 ± 0.04 L · min^{-1}) and t_{LIM} (4.15 ± 0.17 L · min^{-1}), as well as between baseline and t_{END} (4.09 ± 0.17 L · min^{-1}). There was no significant difference between t_{LIM} and t_{END}. There was also a main effect of condition on $\dot{V}CO_2$ ($F_{[3,21]} = 4.463$, $p = .014$). However, *post hoc* testing indicated no significant difference in $\dot{V}CO_2$ between the four test conditions [70%Δ, 80%Δ, 100% $\dot{V}O_{2peak}$, 105% $\dot{V}O_{2peak}$]. There was no significant interaction between time and condition (all $p > .05$).

There was a significant main effect for time on $\dot{V}_E$ ($F_{[1.065,\ 7.458]} = 298.66$, $p < .0001$). *Post hoc* testing showed a significant difference between $\dot{V}_E$ at baseline (40.27 ± 1.79 L · min^{-1}) and t_{LIM} (138.62 ± 6.39 L · min^{-1}), as well as between baseline and t_{END} (136.07 ± 5.84 L · min^{-1}). There was no main effect for condition on $\dot{V}_E$, nor was there a significant interaction between time and condition (all $p > .05$).

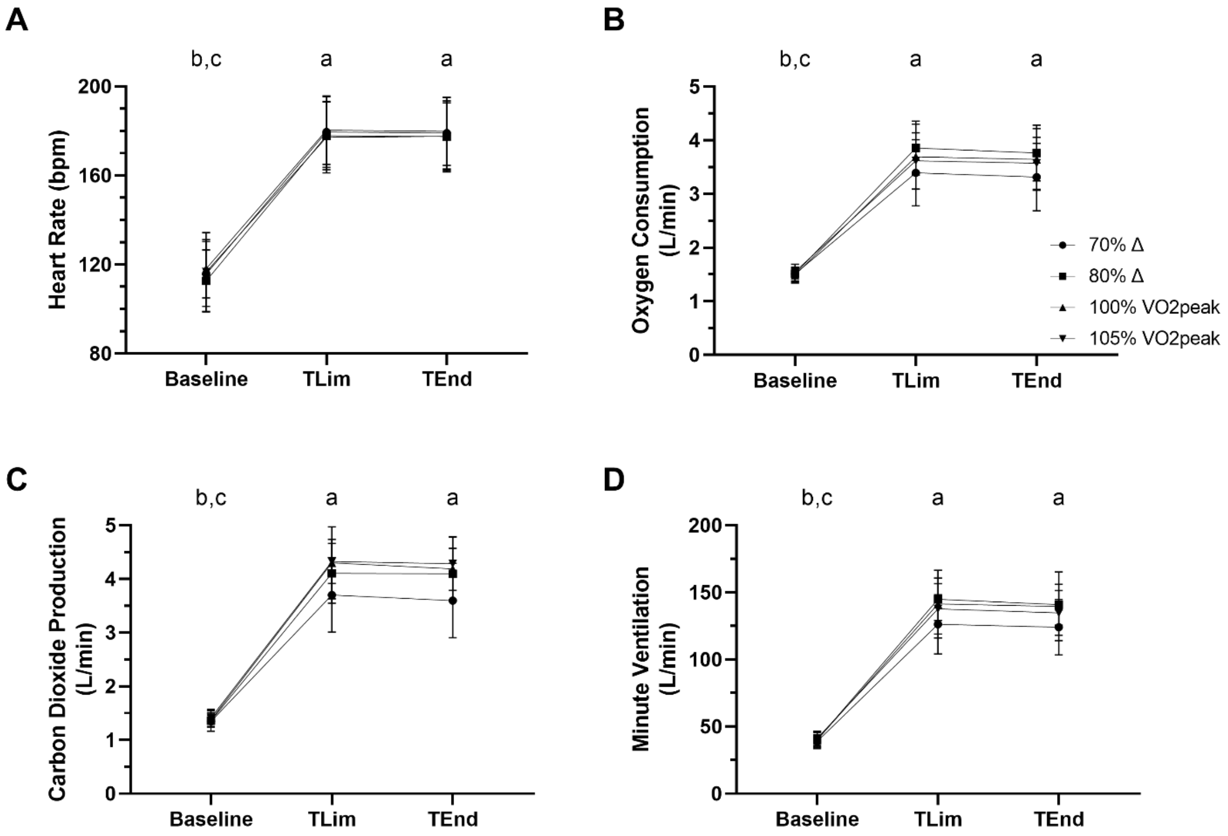


Figure 14. Physiological responses A) heart rate, B) oxygen consumption, C) carbon dioxide production, and D) minute ventilation to the four exercise conditions. a = significantly different than baseline, b = significantly different than t_{LIM}, c= significantly different than t_{END}. Data presented as Mean ± SD.

There was a significant interaction between time and condition on RER ($F_{[2.259,\ 15.812]}$ = 18.00, $p < .0001$). There was a significant main effect for time on RER ($F_{[1.104,\ 7.891]}$ = 369.016, $p < .0001$). *Post hoc* testing showed a significant difference between RER at baseline (0.908 ± 0.010 AU) and t_{LIM} (1.142 ± 0.017 AU), as well as between baseline and t_{END} (1.129 ± 0.017 AU). There was also a significant difference between t_{LIM} and t_{END}. Similarly, there was a main effect for condition on RER ($F_{[3,21]}$ = 19.902, $p < .0001$). Follow up testing indicated significant differences between the 70%Δ condition (1.024 ± 0.011 AU) and 105% $\dot{V}O_{2peak}$ condition (1.112 ± 0.020 AU). There was also a significant difference between the 80%Δ condition (1.025 ± 0.014 AU) and the 100% $\dot{V}O_{2peak}$ condition (1.077 ± 0.019 AU), as well as between the 80%Δ condition and 105%

$\dot{V}O_{2peak}$ condition. There were no significant differences between the 100% $\dot{V}O_{2peak}$ and 105% $\dot{V}O_{2peak}$ conditions (all $p > .05$).

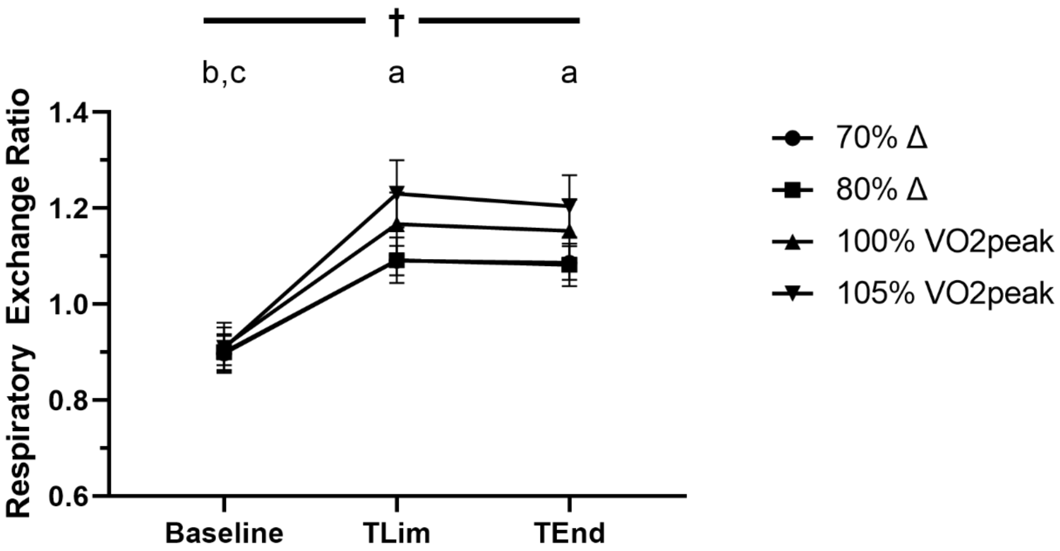


Figure 15. Respiratory Exchange Ratio (RER) for the 4 conditions at baseline, t_{LIM}*, and* t_{END}*.. a = significantly different than baseline, b = significantly different than* t_{LIM}*, c= significantly different than* t_{END}*, † = significant effect of condition. Data presented as Mean ± SD.*

Taken together, the physiological data indicates there was a significant increase in the physiological strain from baseline to t_{LIM}, and that the strain at t_{END} was not different. Participants were working maximally by the time they had reached t_{LIM} and this maximal effort was continued through t_{END}.

5.2.2. Residuals

Upon reaching the limit of tolerance, participants were able to continue performing exercise above CP. There was no significant difference in the magnitude of the residuals when comparing the four test conditions ($F_{[1.70,\ 13.6]} = 2.78$, $p = 0.1031$). However, no significant difference was observed between conditions. The residual capacity for the four conditions (70%Δ, 80%Δ, 100% $\dot{V}O_{2peak}$, 105% $\dot{V}O_{2peak}$) were 329 ± 334, 382 ± 221, 1142 ± 1275, and 1151 ±

1014 J, respectively (Figure 16). Since the work that an athlete performs is proportional to their weight, comparisons between athletes can be difficult to interpret when looking purely at joules of work performed. Thus, the W’ residual capacities were also normalized to each athlete’s total W’, according to equation 5 below:

$$Normalized\ W'_{RES} = \frac{W'_{RES}}{W'_{Total}} \qquad (5)$$

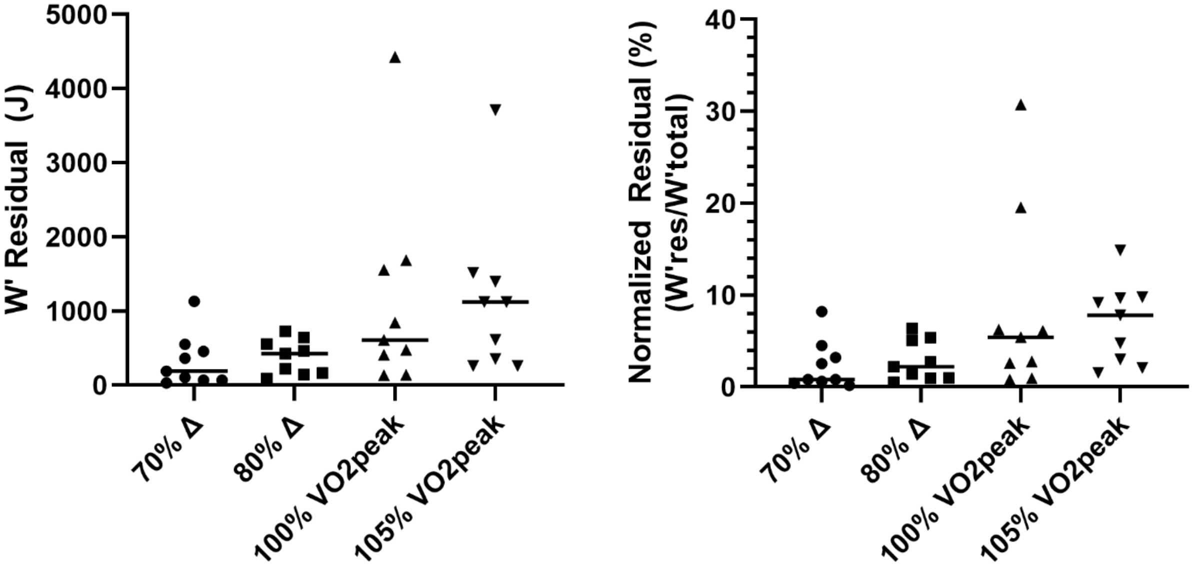


Figure 16. A) raw W’ residuals and B) normalized W’ residuals sorted by test conditions. No significant differences were observed between test conditions. Individual data are displayed with horizontal bar indicating group means.

To ensure that this behavior was not learned, a second Repeated Measures ANOVA was performed to test for an order effect, comparing the size of the residual in the order of the tests were performed. No significant order effect was observed with the raw residuals ($F_{[3,\ 24]}$ = 0.134, p = 0.939).

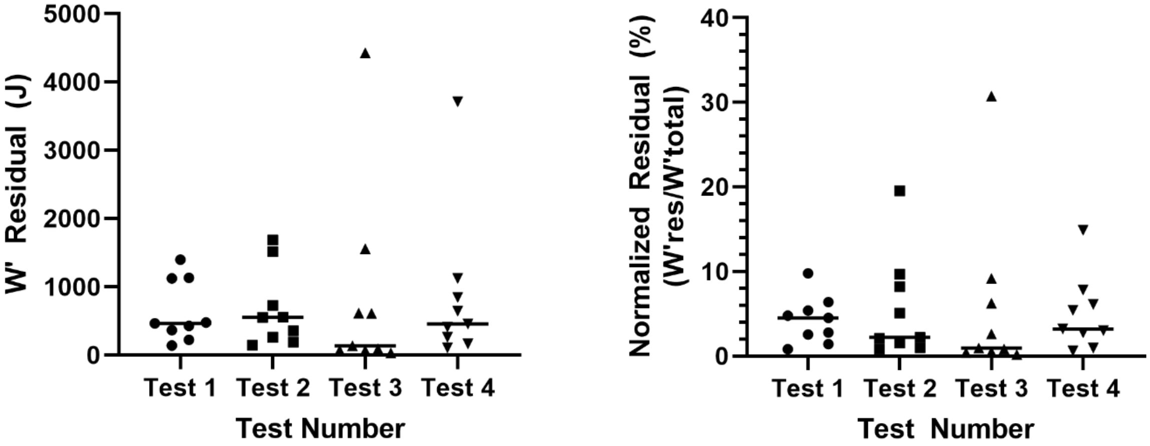


Figure 17. A) raw W' residuals and B) normalized W' residuals sorted by test number. There were no order effects on the size of the W' residuals. Individual data are displayed with horizontal bar indicating group means.

5.3.Modeling of CP and W'

Critical Power and W' were determined by using the linear Work-Time model. Figure 18 demonstrates the how the parameter estimates were determined, using the traditional linear work-time CP model (TRAD) and the modified linear work-time model (MOD). The correlation coefficients for both models were very high (traditional work-time range r^2 = 0.992 – 1.000, modified work-time model range r^2 = 0.992 – 1.000), indicating a good fit of the data.

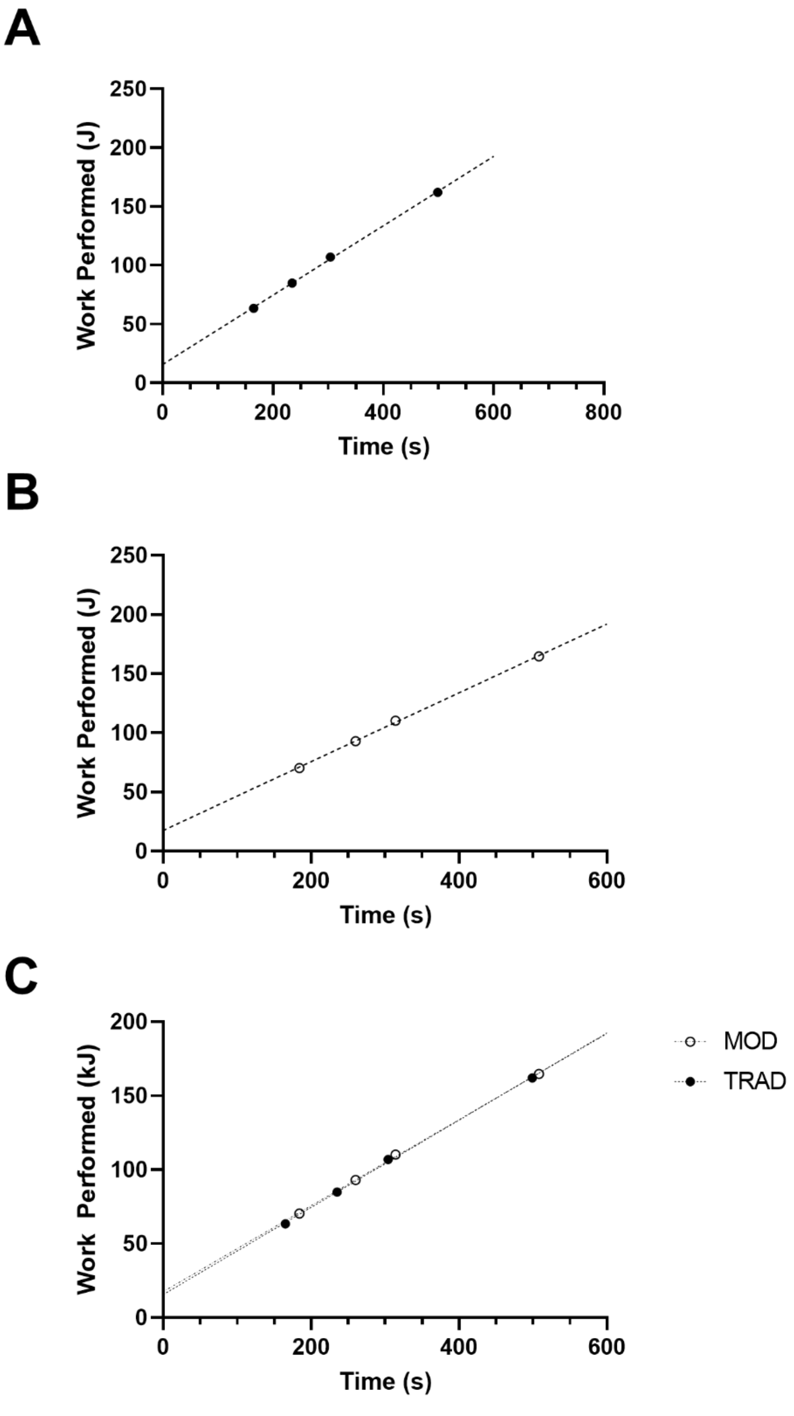


Figure 18. Determination of the CP and W' parameter estimates for the traditional model using the linear work-time model. For the traditional model, the t_{LIM} for each test was plotted against the work performed during the test. B) Determination of the CP and W' parameter estimates for the modified model using the linear work-time model. In the modified model, the total work performed (test work + residual work) was plotted against t_{END}. C) A combined plot of the traditional and modified CP models. Notice the slight deviation of the model at shorter durations.

Critical Power was significantly lower ($t_{[8]}$ = 2.673, p = 0.028; Figure 19 panel A) in the modified protocol [278 ± 14 W] compared to traditional protocol [281 ± 15 W]. Furthermore, W' was also significantly higher ($t_{[8]}$ = -2.981, p = 0.018; Figure 19 panel B) in the modified protocol (17.8 ± 2.4 kJ) than the traditional protocol (15.8 ± 2.0 kJ). Despite smaller changes in some participants compared to others, the trends in CP and W' were observed unidirectionally for all participants.

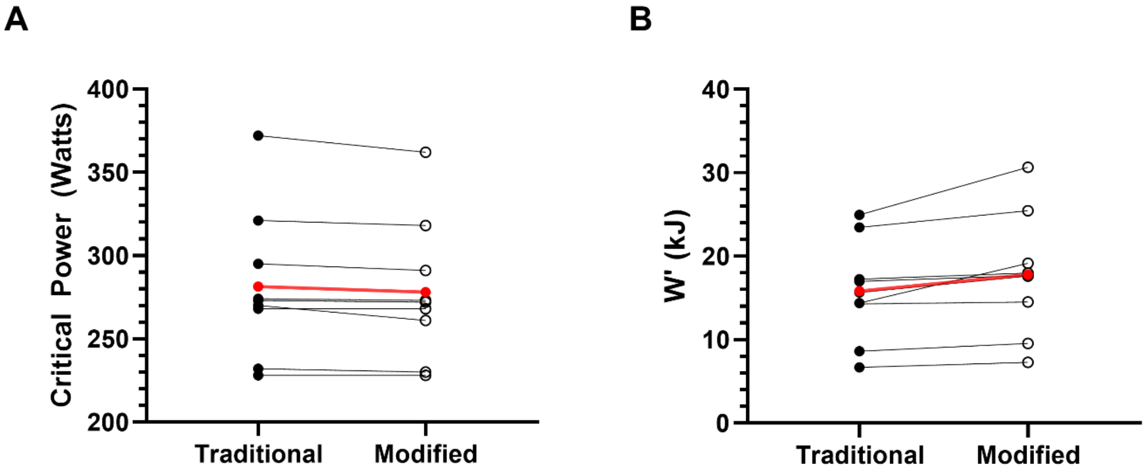


Figure 19. Comparing the A) CP and B) W' parameters determined using the traditional and modified methods. CP was significantly lower (3.3 W) in the modified model compared to the traditional model. W' was significantly higher (1.9 kJ) in the modified protocols compared to traditional protocols. Individual data are displayed with red dots indicating group means.

5.4. Relationship Between W' Residual and Time to Exhaustion

To gain a better understanding about the relationship between the size of an athlete's W' residual capacity and the limit of tolerance, we plotted the normalized residual for each test against the limit of tolerance for each trial of all participants. We observed a negative correlation, where W’$_{RES}$ was larger at shorter durations/higher intensities and became smaller over longer durations/lower intensities. This relationship is demonstrated below in Figure 21.

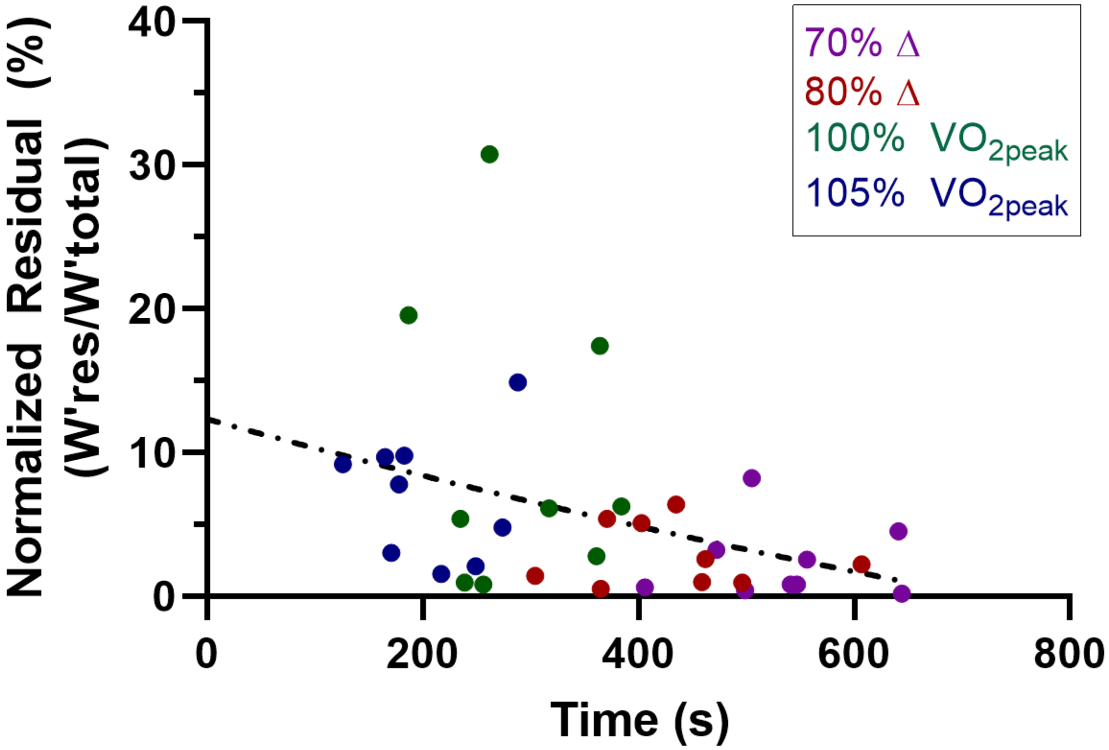


Figure 20. The relationship between the limit of tolerance and W’$_{RES}$. Each point represents a single trial for a single participant. The W’$_{RES}$ was normalized by dividing each W’$_{RES}$ from every trial by the respective participant’s W’. A non-linear relationship between the limit of tolerance and W’$_{RES}$ was observed. Each of the four conditions has been color coded.

5.5. Time to Exhaustion Tests

There was no significant difference in time to exhaustion at the projected 30 MMP$_{TRAD}$ (1078 ± 107) and the projected 30 MMP$_{MOD}$ (1381 ± 274), ($t_{[8]}$ = -1.296, p = .2312; Figure 21). There was no significant difference in success ($F_{[1, 5]}$ = 0.63), intrinsic ($F_{[1, 5]}$ = 0.463), or overall ($F_{[1, 5]}$ = 1.0) motivation between 30MMP$_{TRAD}$ and 30MMP$_{MOD}$ (all p > .05).

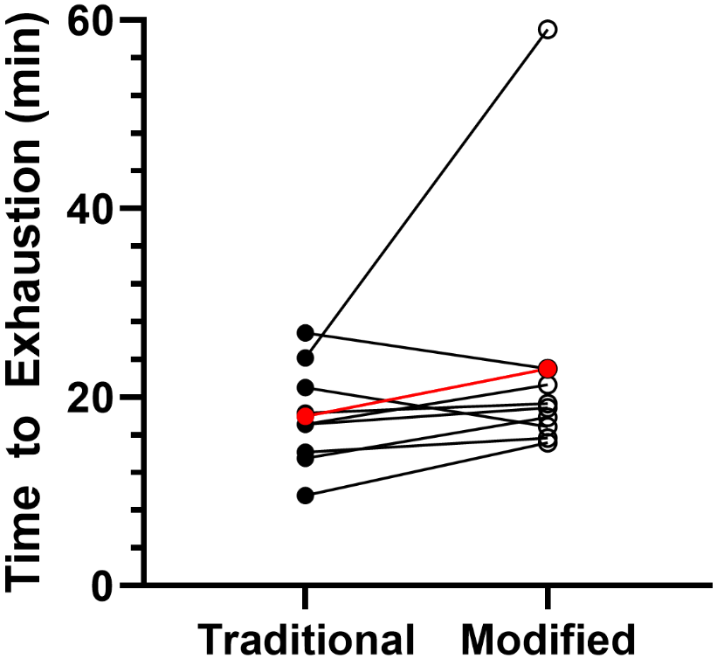


Figure 21. Comparing the traditional 30 MMP time to exhaustion to the modified 30 MMP in minutes. Individual data are displayed with red dots indicating group means.

There was no main effect of the CP model [TRAD v. MOD] when comparing heart rate (bpm) or [La-] (mmol · L^{-1}) (both $p > 0.05$). There was a main effect of time for HR between baseline ((110 ± 16 bpm) and exhaustion (181 ± 7 bpm; $p < 0.001$). Similarly, a main effect was observed between baseline (1.0 ± 0.2 bpm) and exhaustion (12.4 ± 3.4 bpm) when comparing [La-] ($p < 0.001$). There were no differences in RPE between baseline or at exhaustion for the TTE's (all $p > .05$). Results of TTE's displayed in Figure 22 below.

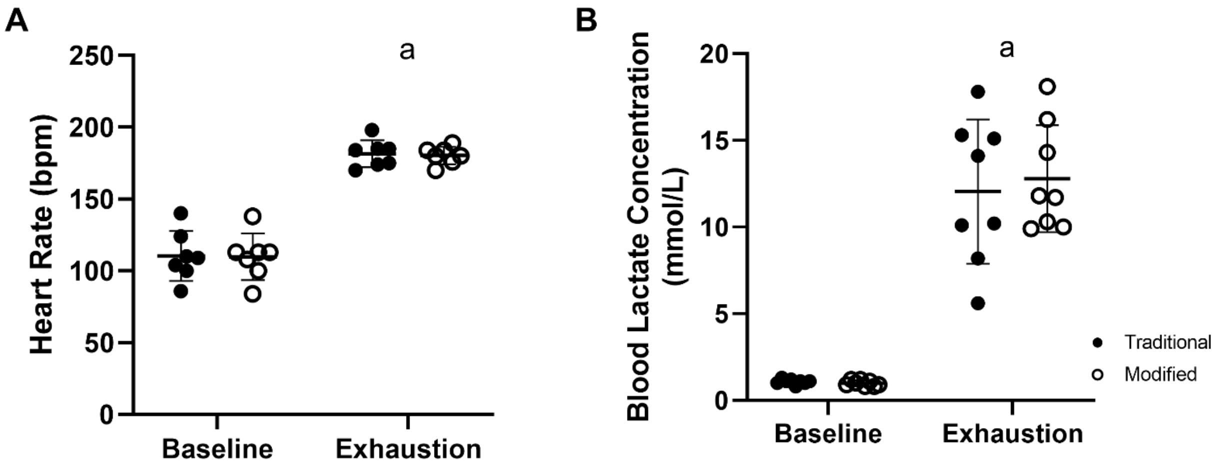


Figure 22. A) Heart rate and B) Blood [La-] concentrations during baseline and at exhaustion for the Tests to Exhaustion at 30 MMP. There was a significant main effect of time, but no significant differences between conditions, indicating participants went all-out during both tests to exhaustion. Individual data are displayed with horizontal bar indicating group means. a = significantly main effect of time.

6. Discussion

The primary objective of this study was to test for a residual capacity above Critical Power upon reaching the limit of tolerance. Secondly, if a residual capacity did exist, what would its influence be on the calculation of the Critical Power and W'? To our knowledge, this is the first study to identify and quantify the residual capacity of athletes to continue performing work above CP after reaching the limit of tolerance. Participants completed four constant power tests to exhaustion, the intensities of which were based upon an incremental ramp test to exhaustion. However, instead of stopping exercise immediately when the limit of tolerance was reached, participants were encouraged to continue exercising while the ergometer resistance was gradually reduced. The primary finding was that participants were indeed able to continue exercising beyond their limit of tolerance when the resistance was reduced, and that the size of the residual capacity appears to be inversely related to the limit of tolerance. Since the depletion of W' is thought to cause termination of high intensity exercise, the ability of athletes to continue working above CP after reaching the limit of tolerance demonstrates that this assumption may not be true.

6.1. Residual Capacity

One of the underlying assumptions of the CP model states that exhaustion or termination of exercise occurs when all W' has been utilized (Monod and Scherrer 1965). This assumption has already been previously challenged – Saltin and Karlsson showed that significant quantities of muscle glycogen remained even after reaching exhaustion (Saltin and Karlsson 1971). Others have suggested that there is a connection between the power demanded at task failure and some “residual” unused fuel supply (Morton 2006). The results of the present study suggest that although the anaerobic capacity (e.g. W’) may be fixed and limited in size, the usable amount is not fixed. Furthermore, if the body does have some residual W’ remaining after reaching the limit of tolerance, then the W’ obtained through traditional CP testing must surely be underestimated.

Although W’ might be fixed in volume, the results of the present study show that the useable amount of W’ is clearly not fixed. If the capacity of W’ truly does limit high intensity exercise, it would be expected that roughly the same volume of work would be performed for all test conditions, regardless of the intensity. However, we found that the total work performed above CP was not consistent for all four durations (Figure 23). This could suggest that the capacity of W’ wasn’t limiting the athletes, but perhaps the *rate* at which W’ was being utilized (i.e. the power output) became limited. Upon reaching their limit of tolerance, participants were able to continue pedaling above CP for all exercise tests, but only when the intensity was reduced. Thus, it appears that neither the capacity of W’, nor its depletion, can explain the cause for muscular failure at the limit of tolerance.

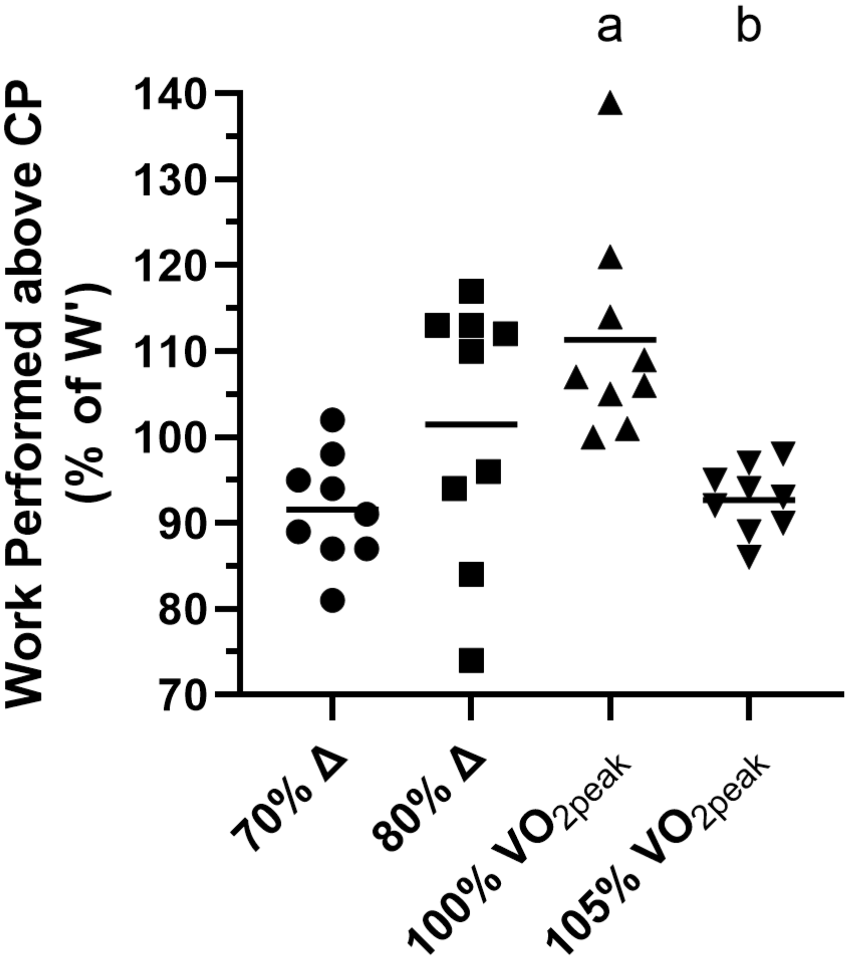


Figure 23. Expressing the work performed above CP from t=0 to t = t_{END} for each of the four conditions. Notice that the four conditions did not result in 100% utilization of their W'. a = significantly different than 70% Δ condition, b = significantly different than 100% V̇O2peak condition. Individual data are plotted with horizontal bars representing the group means.

If the size of the W' does not limit high intensity exercise, what else might? One of the underlying assumptions of the CP model is that W' is finite in capacity but unlimited in rate. In other words, the model expects that all available capacity (in kJ's) can be expended at any point in time. This is certainly not the case, as an athlete with a W' of 20 kJ cannot be expected to produce 20,000 W for 1 second – this is far beyond human physiological limits (~2200 W). Rather it makes intuitive sense that some physiological maximal limit is placed on the rate at which W' can be expended – a Maximum Power Available. In fact, the 3-parameter CP model was developed in part to address this limitation of the 2-parameter CP model (Hugh Morton 1996). The use of a third parameter allows for the calculation of P_{max}, or the maximum instantaneous power that could be produced by an athlete, which must be equal to their physiological maximal power. As fatigue accumulates, it is possible that the ability of the muscle to generate power becomes compromised, resulting in a diminishing maximal power output. The point at which the maximum power which can be achieved is equal to the power demanded for the task results in a point of failure, or what Monod & Scherrer termed the "threshold of local exhaustion". This idea is further supported at the cellular level by the progressive decline in maximal force measured during continuous or repeated tetani in isolated mouse muscle fibers (Allen et al. 2008). It would not be unreasonable for the results seen in these isolated fibers to also apply to whole-body exercise, such as cycling. In fact, the time course of decreases in maximal voluntary cycling power (MVCP) during a constant power time to exhaustion test appears to follow a very similar non-linear trajectory (Figure 24; Marcora & Staiano, 2010).

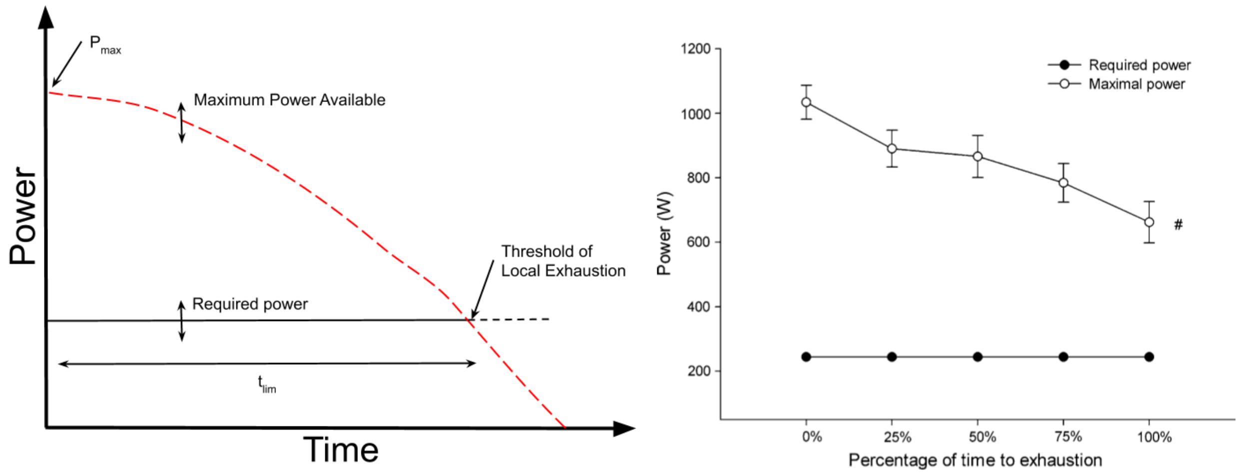


Figure 24. Representation of the gradual reduction in Maximal Power Available from P_{max} during a constant power test. At the threshold of local exhaustion, the participant is unable to maintain the required intensity – this is the point where Maximum Power Available is equal to the task's power output. Beyond the limit

of tolerance, the participant can continue to perform work above CP, but the intensity at this point must be below MPA. Adapted from (Allen et al. 2008).

6.2. Prediction Tests

Importantly, the ability for participants to continue beyond the limit of tolerance was not related to any physiological variable measured in the present study. In fact, no difference was observed between the limit of tolerance and the end of the test in terms of $\dot{V}O_2$, $\dot{V}_E$, or HR. Athletes reached their physiological maximums (HR_{max}, $\dot{V}O_{2peak}$, etc.), and were able to continue pushing past the limit of tolerance while the workload was reduced. Additionally, participants were not informed when they had reached the limit of tolerance – rather, they were simply instructed to hold the predetermined target cadence as long as possible. Finally, there was no order effect across the four trials when comparing the W’ residuals, suggesting that pushing beyond the limit of tolerance was not a learned behavior. Taken together, this suggests that the W’ residual recorded in this study was not a misrepresentation of the limit of tolerance, nor was it a learned behavior.

Another important point to consider is that upon reaching the limit of tolerance, no participants were able to generate more power than the exercise test called for – another indicator that participants had truly reached their limit of tolerance. This result directly conflicts with the findings of (Marcora and Staiano 2010), who found that subjects were able to generate, on average, three times the required power during a maximal voluntary cycling power (MVCP) test upon reaching the limit of tolerance after riding at 80% of peak aerobic power. However, there are several experimental factors to consider when comparing those to the present results. Firstly, the difference in recruited participants may have contributed to some of the differences observed. The present study recruited well-trained, performance level 3 cyclists, compared to recreationally fit rugby players and untrained cyclists. Secondly, no rest was provided to participants in the present study, whereas a brief 3-4s window of unloaded pedaling occurred before the MVCP test in Marcora, et al. This small window of recovery was unavoidable in the study design for Marcora, et al., yet it could explain why participants were able to suddenly generate power exceeding three times the test to exhaustion test power. In the present study, no recovery was permitted for the entirety of the test. A final consideration for comparing the two studies is cadence. In the cited study, participants continued their test to exhaustion until they had reached a cadence that was <40 rpm, at which point the MVCP test was performed. Due to the drastic differences in power output and cadence between the test to exhaustion (power = 242 ± 24 W, cadence = 75 ± 10 rpm) and the MVCP test (power = 731 ± 206 W, cadence = 137 ± 13 rpm), it's possible that the two tasks in Marcora, et al. resulted in recruiting two separate groups of muscle fibers. In the present study, a higher cadence cutoff was utilized in the prediction tests, in accordance with CP testing protocols (Vanhatalo et al. 2007), and no major changes in cadence (and therefore, torque) were permitted. It is unlikely, therefore, that a large shift in muscle fiber type or energy source occurred in the present study.

Interestingly, the exercise tests at a higher intensity (100% $\dot{V}O_{2peak}$ & 105% $\dot{V}O_{2peak}$) displayed a trend for a higher W' residual when compared to the lower intensity tests (70% Δ, 80% Δ) with a large effect size (Fig 16). However, these differences did not reach statistical significance, potentially attributed to a relatively small sample size (n = 9) and a high degree of variation in the size of the W' residual capacities. In fact, time to exhaustion protocols, like the tests used in the prediction trials, tend to have a CV > 10% (Currell and Jeukendrup 2008). Billat et al. also investigated the reliability of a time-to-exhaustion running protocol at an intensity equal to 100% $\dot{V}O_{2peak}$ – identical to one of the test conditions used in the present study – and reported a CV of 17% (Billat et al. 1994). Given the small quantity of residual W' being measured, relative to total W' (approximately 0.2% to 30% of W'), it is possible that the W' residual capacity recorded could be due to the variability of the test itself. Further studies should consider investigate the repeatability of the W' residuals.

6.3. Difference between TRAD and MOD Models

While it is possible to model Critical Power to a single Watt, it is unreasonable to think that the value of CP is absolute. Instead, there is inherent biological variability which has been estimated around ± 3-5% (Jones et al. 2019) following careful attention to experimental protocol. We observed a significant 3.3 W (1.2%) decrease when accounting for the W' residual capacity. Although the mean change in CP falls within the biological variability margins of the existing model, the unidirectional trend for all participants may suggest that the traditional model did overestimate the Critical Power. It has been reported that the Critical Power is approximately 7% higher than MLSS (Smith and Jones 2001; Pringle and Jones 2002; Dekerle et al. 2003, 2005; Keir et al. 2015; Mattioni Maturana et al. 2016), on average. Accounting for this residual capacity did bring CP closer to physiological markers of the maximal steady state, such as MLSS.

Since participants were able to continue working above CP after reaching the limit of tolerance, the statistically significant increase in W' (+ 1.95 kJ, 12.4%) is unsurprising. Not only were participants able to continue exercising above CP upon reaching the limit of tolerance, but the total residual work performed above CP also appears to be related to the intensity of the exercise test. There was an inverse relationship between the limit of tolerance and the residual W' capacity of the tested participants (Figure X). A non-linear response where W'_{res} approaches

0 J at longer durations would make sense intuitively because W’ certainly has a finite capacity. Additionally, the higher the intensity of the test (and thus the shorter the duration), the greater the gap between the test power and CP, and therefore the greater potential for W’ residual work to be performed.

The changes in CP and W’ observed in the present study are drastically smaller than the changes reported by Morton, 1996, who attempted to address the limitations of the CP model by introducing a non-zero time constant (asymptote) in the 3-parameter CP model. By introducing a time constant that was less than 0, he saw a substantial and statistically significant 96% increase in AWC (W’) and -7.6% decrease in CP (Hugh Morton 1996). These changes far exceed the changes seen in the present investigation (1.2% for CP, +12.4% W’). However, for some athletes, the 3-parameter model resulted in W’ values that are likely well outside physiological possibility (e.g. 129.3 kJ). In the present study, we observed more moderate, yet statistically significant changes in both W’ and CP. These changes were also consistent in directionality with the changes observed by Morton, with CP trending to decrease and W’ trending to increase.

6.4.Time to Exhaustion

Despite the statistically significant changes in both CP and W’, we observed no statistically significant change in the ability of participants to perform at the model’s predicted 30-minute power output. However, athletes averaged a 28.1% increase in time to exhaustion at what the model predicts for 30-minute power yet were still well short of predicted 30 minutes. After the adjustments in CP and W’, athletes still averaged only 23 min at what the model predicted was sustainable for 30 minutes. This supports the results of Pallarés, et al, who found that CP model overestimated TTE at MLSS by 6% (Pallarés et al. 2020). We found that TTE at 30 min power was overestimated by 40.1% with the traditional CP model, and still overestimated by 23% with the modified CP model. It is possible that we experienced a greater overestimation since the power output tested in the present study (290 ± 43 W 30 MMP_{TRAD}; 288 ± 42 W $30MMP_{MOD}$) was significantly higher than the power at MLSS (247 ± 20 W).

6.5. Functional Significance of Modified Method

The Critical Power model can be used to estimate the time to exhaustion for any power output exceeding CP (Equation 1). However, as it stands, the parameters CP and W' can only be used to identify when the limit of tolerance is reached (i.e. the Threshold of Local Exhaustion), not when total exhaustion is reached. The current model is unable to predict how the power-duration changes as peripheral fatigue is accumulated by an athlete. We showed that athletes still have a capacity to perform work above CP, even after reaching the threshold of local exhaustion. However, describing the dynamics of how muscles fatigue beyond the threshold of local exhaustion is outside the realm of the current project, and is something that should be explored in future studies.

6.6. Limitations

This study is not without limitations. First and foremost, the results of this study are heavily dependent upon maximal efforts to exhaustion. The reasons for termination of exercise are still heavily debated in the research literature between peripheral (muscle metabolic waste, $\dot{V}O_2$ delivery, etc.) and central fatigue (motivation, self-talk, etc.). Neither the CP model nor the results of the current study attempt to differentiate between central and peripheral fatigue.

Instead, the combined effects of central and peripheral fatigue are what matter from a functional perspective. We attempted to minimize this using familiarization sessions, where participants were familiarized with the testing procedures.

Secondly, the sample of athletes from the present study are rather heterogeneous, containing athletes with a wide range of age (19 – 55) and performance ($\dot{V}O_{2max}$ range 41 – 69 mL · kg^{-1} · min^{-1}). We attempted to minimize the variation in the population by limiting the recruited participants as a category 3 cyclist, according to the review by De Pauw, et al. A larger pool of athletes had been recruited (*n* = 17), however only 9 participants were able to complete the full protocol prior to the COVID-19 lockdown.

The use of maximal tests to volitional exhaustion as a performance metric might be considered another potential limitation of the current study. Due to the constant power output of the TTE used in this study, it is less ecologically valid and more variable (26.6%) than a self-paced time trial (Currell and Jeukendrup 2008). Despite this consideration, accounting for the changes in CP and W' resulted in a 28% improvement at the predicted 30-minute power for the modified CP model, relative to the traditional model (Figure 21).

Another consideration of this study is that use of a Velotron electromagnetically braked ergometer has not been validated for all Critical Power testing. To the authors' knowledge, this is the first study to utilize the Velotron for Critical Power testing. More specifically, the power from the Velotron is calculated from flywheel speed, rather than direct strain gauge measurement. Despite this, the Velotron has been previously tested for anaerobic power measurement (Astorino and Cottrell 2012). To create an environment that would allow participants to continue pedaling beyond the limit of tolerance without directly controlling their power output, the manual course mode in the RacerMate One™ Power Training software program was used. Since the Critical Power tests to exhaustion were performed in course mode, participants were able to continue pedaling beyond the limit of tolerance. This also means that controlling the power output during each of the prediction tests is dependent upon a consistent cadence during the test. Major variations in cadence could directly influence the power output during a test. Variation in cadence during the tests was minimized through the use of a familiarization trial, as well as verbal and live visual feedback.

Finally, it is typical that the prediction trials to exhaustion are used to derive CP using the hyperbolic power-time model, the linear work-time model, and the linear power-time^{-1} model (Vanhatalo et al. 2007), and the model resulting in the lowest total error (%CV) in CP & W' is used for parameter estimation. However, only the linear work-time model was used to derive CP in the present study. This model was used because it is the only model of the three which relies on the relationship between total work performed and duration. We reason that the use of a power-time model, such as the hyperbolic power-time or power-time^{-1} are not appropriate when the power of the test is not constant throughout.

6.7. Future Considerations/Directions

The field of performance modeling is still relatively new, as the hardware (power meters, GPS cycling units) and software continue to develop at a rapid pace. Based on the results of the present study, as well as observations by others, there are a few key areas that need further research:

- What are the dynamics of the power-duration relationship once the limit of tolerance has been reached?

- Do the results displayed in the present study hold true in other populations? (e.g. elite/professional athletes)
- What other factors are limiting performance besides the capacity of W’?

6.8.Conclusion

In conclusion, athletes can continue producing work above CP, even after reaching the limit of tolerance while doing constant work rate CP testing. Despite a non-significant difference in residual between test conditions, there was a large effect size for the size of the residual relative to the limit of tolerance. The idea of a residual capacity could fundamentally change the way in which CP testing is performed and change our understanding of how human performance is modeled. Since we have provided evidence suggesting the capacity of W’ is not limiting an athlete’s power output during high intensity efforts, perhaps there is another parameter which could be added to the model which would allow for the calculation of an intermittent maximal instantaneous power. In fact, Baron Biosystems has developed a novel model which features a “Maximal Power Available (MPA)”, which represents the maximum power that an athlete could generate at any point in time. Future studies should look at validate the results of the present study, as well as determine the repeatability of the W’ residual capacity and determine how to accommodate this residual capacity within the existing CP model, if possible.

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