# REVISITING THE POWER-DURATION RELATIONSHIP AND DEVELOPING ALTERNATIVE PROTOCOLS TO ESTIMATE CRITICAL POWER PARAMETERS 

by

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# Revisiting the Power-Duration Relationship and Developing Alternative Protocols to Estimate Critical Power Parameters 

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Critical Power concept is used extensively in sport to characterize an individual's fitness by estimating the anaerobic and the aerobic component of the energy system, anaerobic work capacity (W') and Critical Power (CP). The model makes an assumption that all types of athlete have the same pattern of responses when it comes to power and time to exhaustion, however recent study showed different observation. Therefore, a more generalized model was proposed with a relationship constant, n , that can freely describe the relationship and the model demonstrated no difference between types of athlete across swimming ( $\mathrm{n}=0.29$ ) and cycling ( $\mathrm{n}=0.48$ ), but the relationship is significantly different from traditional assumption ( $\mathrm{p}<0.0001$ ).

The traditional method of deriving CP and $\mathrm{W}^{\prime}$ requires repeated, time consuming tests. Alternatively, a 3-min all-out test (3MT) yields good estimates of $\mathrm{W}^{\prime}$ and CP . However, adoption of the 3-min protocol for regular fitness monitoring is deterred by the mentally/physically strenuous nature of the test. Therefore, two alternative protocols, shorter all-out test and Constant-Power + all-out test (CPT) were proposed to measure W' and CP parameters accurately. After adjusting for weight differences between sex, 150 s all-out test duration produced parameters for sprint and endurance athletes which did not
differ from longer duration tests $>3$ min when compared to the 3MT (3-6 min test $\mathrm{p}=0.0052,>6$ min test $\mathrm{p}<0.0001$ ) while for $\mathrm{W}_{\mathrm{e}}{ }^{\prime}$, only $>6$ min duration showed a significant difference from the $3 \mathrm{MT} \mathrm{W}{ }_{\mathrm{e}}(\mathrm{p}=0.0065)$. Therefore, CPT with time duration less than 3 min could be an alternative protocol to estimate CP parameters.

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## 1 Introduction

Endurance athletes are constantly being monitored through physiological tests to accurately determine their cardiovascular and muscular endurance fitness to optimally define their individualized training needs. Several methods, such as $\mathrm{VO}_{2}$ max testing (a ramp test involving the use of a face mask to collect expired gases for analysis) [1], lactate threshold testing (where blood samples may need to be taken) [2] used to assess fitness currently exist, but have important shortcomings. These tests can be cumbersome ( $\mathrm{VO}_{2} \max$ ), invasive (lactate threshold test), expensive and disruptive to an athlete's structured training schedule. Furthermore, the access to these tests is generally limited only to high performance and elite athletes. Hence, a simple technique is necessary to help athletes of all abilities monitor their fitness status.

A mathematical model can be used to describe one's fitness state through a suitable set of parameters. The duration dependency of mechanical power in the Critical Power concept has been well characterized for humans, which presents itself in a general negative exponential relationship. The steep initial decrease in performance during 2 to 30 seconds is much larger than those occurring during 30 to 60 seconds and exceeds those taking place from 1 to 2 minutes, etc... This decrement in performance continues to durations beyond 10 minutes to an eventual asymptotic level, at which time the body's renewable aerobic sources of energy alone can sustain the demand.

The Critical Power model was initially proposed by Monod and Scherrer [3], first in the investigation of small muscle groups and then later extended to whole body exercise by Moritani et al. [4]. A hyperbolic relationship was reported between power output (P) of different exercise intensities and their respective time to exhaustion ( t ). The aerobic component is called Critical Power (CP), and theoretically represents the power output that one could maintain indefinitely without reaching exhaustion. The anaerobic component is called anaerobic work capacity (W'), and theoretically represents a finite supply of energy that is used at intensities greater than Critical Power, such that
exhaustion would be a consequence of total $\mathrm{W}^{\prime}$ depletion. The model can be represented mathematically as:

$$
\begin{equation*}
P=\frac{W^{\prime}}{t}+C P \tag{1.1}
\end{equation*}
$$

The model has been routinely applied to cycling [5], running [6, 7], swimming [8], rowing $[9,10]$ and racquet sports such as table tennis [11]. The practical application of the CP model is limited by the physically demanding nature of the traditional protocol and the need for subjects to perform 3-5 all-out exhaustive exercise tests [12-16]. This impractical protocol can take upwards of 1-1.5 week to complete depending on the number of tests performed and with recovery periods lasting 30 minutes [17], 12 hours [18], or 24 hours [13-16] between all-out efforts.

Several models have been proposed to address the limitations stemming from the assumptions of the model. Implicit assumptions include aerobic energy being unlimited in capacity (i.e. one could exercise at an intensity at or below Critical Power for an indefinite amount of time), and anaerobic energy being limited in capacity, but not rate limited (ie. maximum power output is infinite). Other assumptions that can be inferred from this model are that power output is a function of two energy sources, aerobic and anaerobic, and that exhaustion occurs when W' is depleted [19]. Morton attempted to address the assumptions that maximal power output is infinite and that exhaustion occurs at depletion of W' by creating a three-parameter CP model [20]. Wilkie introduced a delayed aerobic supply correction factor to account for the delay in aerobic supply for oxygen uptake kinetics [21]. Morton proposed a 3-energy system model that comprises three energy systems, phosphagen utilization, anaerobic glycolysis, and aerobic power [22]. A more complex extension was proposed by Péronnet and Thibault that involves both kinetic delays in aerobic power supply, and the progressive reduction of aerobic power required to sustain for exercise durations over 7 minutes in length [23]. Several other sophisticated models have been proposed, however, despite the improvements that
were made, these more complex models were not widely employed and investigators resorted to the CP model for its simplicity.

To address the shortcoming of the time consuming multi-day protocol as traditionally required for the CP model, a promising protocol that has been gaining popularity based on the premise that anaerobic capacity can be predicted from one all-out exercise test lasting $90-120 \mathrm{~s}[24,25]$, a $3-\mathrm{min}$ all-out test (3MT) was proposed [26, 27]. The 3MT estimates CP model parameters based on the rationale that once W' is fully depleted after 90-120 s, the remaining maximum power output (termed End test Power, EP) should be equal to CP [27]. The estimates from the 3MT were validated with the estimates derived from the traditional CP model [27, 28], and reliability analysis showed that repeated 3MT can provide reliable CP and W' estimates [29, 30]. One training intervention study has shown that 3MT can reflect the training induced changes in CP [29]. This demonstration of sensitivity to change has a significant practical application in monitoring adaptation to training. Moreover power-duration based training intensity zones have been created using 3MT end power to allow constant monitoring of training progress [31].

Despite the appeal of the 3MT, the mentally and physically exhaustive nature of the test deters repeated testing occurrences. Thomas et al. (2012) reported that adopting an evenpacing strategy (constant work-rate tests) reduces the perception of exertion compared to self-paced (aggressive-paced) strategy [32]. de Koning et al. (2011) theorized that RPE at any given time point is dependent on the magnitude and rate of homeostatic disturbance and the fraction of duration or distance remaining. In other words, a fast start would result in higher reported RPE values for the entire race resulting in an increased "hazard of catastrophic collapse" [33]. This drawback is one of the reasons that impair our ability to use the 3 MT as a regular fitness-monitoring tool. Consequently, this approach to estimating fitness components is not widely used. Therefore, there is a need for a less physically and mentally exhausting protocol to measure aerobic and anaerobic components.

All of the models proposed to date have made the assumption that the performance to time response is the same for all type of athletes (sprint or endurance). However, a recent observation made by Bundle showed that the relationship between exercise performance and duration differs fundamentally between sprint and endurance exercise [34].

Therefore, an investigation is warranted to revisit the relationship between power output and time to fatigue with the theory that the relationship will be different for individuals involved in sport that is dominated by anaerobic or aerobic energy generating systems.

Test duration may be influenced by the balance between $W^{\prime}$ and CP. Sprint-trained athletes produce supra-maximal anaerobic outputs rapidly while endurance-trained athletes are expected to perform at moderate to high submaximal (aerobic) rates for long durations [35, 36]. We demonstrated that those differences are reflected in a significantly higher $\mathrm{W}^{\prime}$ and lower CP in a group of sprint athletes compared to endurance athletes [37]. The differences in $\mathrm{W}^{\prime}$, CP , and the curvature of the power-time relationship suggests that shorter all-out test durations could accurately quantify CP . If shorter test durations can be employed then athletes would experience less discomfort than is associated with the 3MT.

In this document, I will introduce the Critical Power concept and highlight the key differences in some of the extensions to the Critical Power model. A slightly modified Critical Power model will be proposed to better describe the power-time relationship. Three studies in total were conducted. The first study delves into the relationship CP model in order to compare the goodness-of-fit of the power-duration relationship between the proposed model and the traditional CP model, and to investigate the power-duration relationship between different types of athlete in the sports of swimming and cycling. The second study investigated the shorter duration in an all-out test to determine the duration required to estimate the CP model parameters for sprint and endurance athletes. Lastly, the final study examined the Constant-Power all-out test, which aims to develop a single test protocol that can accurately estimate CP parameters while addressing the drawbacks of the time-consuming protocol of the traditional Critical Power model and the physically and mentally exhausting nature of the 3-min all-out test.

## 2 Background / Review of the Literature

The Critical Power concept has been studied for decades but has not been widely used outside of laboratory settings mainly due to the high cost of the power measuring devices. However in the recent years, the utilization of the Critical Power model has gained popularity with the increased in commercialization of affordable portable power meters for bicycles and global positioning system (GPS) watches/computers. GPS systems calculate speed based on the 3D positions (latitude, longitude, and altitude) determined from the signals of the satellites. Several factors (such as atmospheric) can affect the accuracy of the GPS receiver accuracies but in general the receivers are extremely accurate to within an average of 15 meters [38]. On the other hand, most cycling power meters use strain gauges to detect deformation in the measured part in order to calculate power output. There are four main areas on the bike that power meters measures the power output from: rear wheel hub, crank spider, crank arm, and pedals. The accuracies of the power meters range from $\pm 1.5-2 \%[39,40]$. It is with this emergence of these affordable and portable monitor measuring devices that makes it is now possible for athletes/coaches to use the Critical Power model to monitor training more precisely.

In this section, the Critical Power model and its variations are presented and discussed. The two parameter estimates, Critical Power (CP) and anaerobic work capacity (W') are compared to laboratory markers for validity. Furthermore, several interventions used to alter CP and W' individually are discussed. Extensions of the CP model are also presented to show the different directions that investigators have been embarking on over the years. Lastly, a modified CP model that is better able to describe the relationship between performance and time is proposed that calls for more in-depth investigations into different types of sports/athletes.

### 2.2 Critical Power Model

The Critical Power model was first introduced by Monod and Scherrer in 1965 to describe the relationship between maximum total work done $(W)$ by small muscle groups and the time it takes before they are exhausted $(t)$. A linear relationship was observed and can be represented as,

$$
\begin{equation*}
W=W^{\prime}+C P \cdot t \tag{2.1}
\end{equation*}
$$



Figure 2.1 Work-time relationship
Critical Power (CP) is defined as the power output that could be maintained indefinitely and without exhaustion (theoretically). Anaerobic work capacity ( $\mathrm{W}^{\prime}$ ) is a measure of anaerobic energy capacity. This energy is available on demand and can be utilized as quickly or as slowly as required, however the ability to sustain efforts above CP fails when the reserve is completely depleted.

This model was extended by Moritani et. al. in 1981 to whole body dynamic exercise with the similar linear relationship being observed [4]. The original linear work-time model (2.1) can be rearranged to yield two other mathematically equivalent models that have been used by researchers to derive estimates of the parameters of the relationship ( CP and $\mathrm{W}^{\prime}$ ). Dividing the original model by $t$ yields the linear power vs. $1 /$ time model [15, 41-43],

$$
\begin{equation*}
P=\frac{W^{\prime}}{t}+C P \tag{2.2}
\end{equation*}
$$



Figure 2.2 Power-1/time relationship
This extension of the CP concept to whole-body exercise led to a few assumptions [44]. There are only two components to the energy supply system for human exercise: an aerobic component that is unlimited in capacity but is rate-limited, termed Critical Power (CP), and an anaerobic component that is limited in capacity but is not rate-limited, termed Anaerobic Work Capacity (W'). Exercise at an intensity level above CP stops upon depletion of ${ }^{W}$ '.

A more intuitive and preferable version from an exercise performance point of view is the nonlinear time-power model (for $\mathrm{P}>\mathrm{CP}$ ), in which time $(t)$ is the obvious dependent variable as it is dependent on the power output of the test and power output $(P)$ is the explanatory variable [45],

$$
\begin{equation*}
t=\frac{W^{\prime}}{P-C P} \tag{2.3}
\end{equation*}
$$



Figure 2.3 Nonlinear time-power relationship

From this equation, two assumptions are implicitly made. The first assumption is that time will be infinite for $P<C P$, and the second is power output will be finitely large as time approaches zero (i.e. Peak power). Other assumptions that can be inferred from this model are that aerobic power is available from the beginning of exercise and is available at the same rate (CP) until exercise ends, heat and other physiological by-products are not accumulated, and that $\mathrm{W}^{\prime}$ and CP are constants independent of power output and/or time.

Historically, in order to estimate the values of anaerobic work capacity and Critical Power parameters, an individual had to perform more than two (generally four to five) constant power tests to exhaustion. Housh reported that CP estimates derived from two predicting tests were highly correlated with the CP estimates derived from four predicting tests and that the standard errors for the estimates were very low [17]. However an outlier would have substantial effect on the estimates of the parameters. Therefore Poole suggested using at least four or five predicting trials to allow precise identification of the parameters [46]. Values of power are generally chosen for each individual, so that the time to exhaustion occurs in a range of 1 minute to 10 minutes [13]. Goodness of fit is rarely reported, however, data are statistically fitted with one of the three Critical Power models to obtain the parameter estimates that characterize the aerobic and anaerobic component for each individual.

### 2.2.1 Critical Power Parameter

In theory, the CP parameter provides an estimate of the power output that can be sustained for a very long time without fatigue [3, 4], and it represents the aerobic energy supply system [15]. Several researchers have tried to validate and explain the CP parameter by making comparisons with other aerobic indicators. Mean CP power output $(230 \pm 22 \mathrm{~W})$ was reported to be $28 \%$ higher than power output associated with the lactate anaerobic threshold $(180 \pm 32 \mathrm{~W})$ from the work-time model [47], and the CP parameter derived from the power-1/time model showed a 13\% higher mean value ( $265 \pm$ 39 W ) than the mean individual anaerobic threshold value ( $235 \pm 44 \mathrm{~W}$ ) [48]. The CP was initially reported to have the same value as the ventilatory anaerobic threshold [4], but Poole showed that CP is significantly higher than (64\%) the mean ventilatory anaerobic threshold ( $197 \pm 12 \mathrm{~W}$ vs. $120 \pm 8 \mathrm{~W}$ ) [46, 49].

In addition to making comparisons to CP against metabolic thresholds, several investigators have questioned the hypothesis that CP can be kept up for a very long time without fatigue. A number of studies were proposed to investigate prolonged exercise at each individual's estimated CP. Housh [42] observed that subjects could maintain CP for a mean time of 33 minutes, and this finding was corroborated by Jenkins and Quigley [17] and McLellan and Cheung [48] in separate studies. Pringle [50] found that CP occurs at a similar intensity to the maximum lactate steady state, suggesting that it represents the highest exercise intensity that can be maintained from only oxidative ATP production, and separates the heavy from severe exercise intensity domains [13, 44, 50, 51], as shown in Figure 2.4.


Figure 2.4 Power-time relationship illustrating the location of different aerobic markers relative to CP (adapted from [52]), W' at each point is constant which is represented by the shaded rectangular area.

### 2.2.2 Anaerobic Work Capacity Parameter

The other parameter of the Critical Power model, $\mathrm{W}^{\prime}$, provides a measurement of the anaerobic reserve of the individual. This amount of energy released by complete utilization of the anaerobic stores (oxygen stores, high energy phosphates, and anaerobic glycolysis) is assumed to be constant and its total depletion would induce exhaustion [53, 54]. In comparison to aerobic contributions of the CP model to exercise, the anaerobic energy component has received relatively few investigations in the field of applied physiology. $\mathrm{W}^{\prime}$ is considered by many authors to be an index of anaerobic capacity [44, 55, 56]. W' determined by the Critical Power model has been compared to numerous indices of anaerobic capacity such as the Wingate test [18, 57, 58], work performed during predominantly anaerobic exercises $[18,44,55,57-59]$, and maximal accumulated oxygen deficit (MAOD) [25].

The results from the studies comparing $\mathrm{W}^{\prime}$ derived from the work-time relationship and work performed in a 30 -second Wingate test suggest that they are related with a correlation coefficient of $0.65-0.75$. However, the validity of a 30 -second test has been challenged [60] by arguments stating that the test is too brief to tap into the glycolytic system completely [61], and that a considerable amount of anaerobic energy is still
available at the end of the test [58]. W' has been observed to correlate well with other indices of anaerobic capacity such as work performed during predominantly anaerobic exercises ( $\mathrm{r}=0.70-0.74$ ) $[44,55,57,58]$ and with MAOD [25], which is a widely accepted measure of anaerobic capacity [60]. Nevertheless, in these anaerobic tests, there is a significant aerobic contribution which will be discussed in the next section.

It has been suggested the capacity of $\mathrm{W}^{\prime}$ is dependent on the extent of the severe domain, defined as the difference between CP and $\mathrm{VO}_{2} \max$ intensity [62, 63]. The extent of the severe domain will also dictate the magnitude of the $\mathrm{VO}_{2}$ slow component, which is measured as a progressive increase of $\mathrm{O}_{2}$ cost as severe-intensity exercise proceeds. The occurrence of the slow component is associated with the onset of lactate accumulation [64-66] and is related to a loss of muscle contractile efficiency [26], linking them to the process of muscle fatigue $[67,68]$.

### 2.2.3 Interventions That Alter the CP and $\mathrm{W}^{\prime}$

CP parameters can be altered in one of the two ways, alteration (eg. training interventions, creating loading, and priming) or accessibility (eg. pacing). Few interventions such as training, prior "warm up" exercise, and creatine loading have been shown to alter W' and CP parameter estimates [13, 15, 62, 69, 70]. CP increases after a short period (4-6 weeks) of endurance training [70] and after high-intensity interval training [13, 15, 62], while $\mathrm{W}^{\prime}$ is reduced after previous high-intensity exercise [68, 69, 71]. Only one investigation has achieved a significant increase in $W^{\prime}$ ( $49 \%$ ) following "all-out" sprint-interval training [59]. W' also tends to decrease after training interventions that increase the CP $[62,70]$. Prior heavy-intensity exercise reduces the time to reach $\mathrm{VO}_{2 \text { max }}$ in very high-intensity exercise ( $>100 \% \mathrm{VO}_{2} \mathrm{max}$ ), which tends to increase the magnitude of the W' [72]. In addition, positive effects of creatine loading are evident in increased W' after acute supplementation (2-7 days) [73, 74], however, a 30 day creatine loading period did not affect $W^{\prime}$ [75].

Apart from training, the accessibility of $\mathrm{W}^{\prime}$ may also be altered by pacing strategy. A fast-start pacing strategy, which speeds the overall rate of increase in $\mathrm{VO}_{2}$, has been
linked to significantly greater work done above CP (ie, $\mathrm{W}^{\prime}$ ) compared with even-paced and slow-start pacing strategies during three min of high-intensity exercise [76].

Inspiration of hyperoxic gas during exercise is associated with a reduced slow component and improved high-intensity exercise tolerance [77]. Few studies have manipulated the inspired $\mathrm{O}_{2}$ fraction to investigate its effects on the power-time relationship. CP was shown to be a parameter of oxidative function, where hyperoxia increased $\mathrm{CP}[4,63]$ and maybe reduced hypoxia [4]. Surprisingly, hyperoxia reduced W' [63] and hypoxia showed no effect on W' [4]. There was an inverse correlation between changes in CP and W' $(\mathrm{r}=-0.88)$, and this finding contradicts the definition of the W' parameter as a fixed anaerobic capacity [63]. The consequence of cycling pedal cadence on the parameters of the power-time relationship has also been investigated, showing lower CP values at higher cadence, while W' showed the opposite [78, 79]. The interrelated physiological nature of CP and W' makes interpretation of these results challenging. Therefore, interventions specifically aimed at altering each CP parameter individually may be overly simplistic [52].

### 2.3 Extensions of the Critical Power model

Several applied physiologists recognize that the relationship between power output and time to exhaustion is not as simple as the inverse model. It fails if it is used to describe a more detailed study of the physiological mechanisms of muscular work and fatigue, or to predict time to exhaustion for very high or low values of power output. Some of the factors to be considered for a model extension may include components that represent each of the three fuel sources or the kinetic delay in availability of one or more of each fuel type.

The allocation of energy for exercise from each energy transfer progresses along a continuum. At the high intensity region, the intramuscular high-energy phosphates supply almost all of the energy for exercise. The ATP-PCr and lactic acid systems supply about half of the energy for intense exercise lasting 2 minutes, and aerobic systems supply the remainder of the energy. Intense exercise of intermediate duration lasting 5 to

10 minutes places greater emphasis on aerobic energy transfer. Longer-duration exercises require a constant aerobic energy supply with little contribution from anaerobic sources. Figure 2.5 illustrates the relative energy system contribution to the total energy supply for any given duration of maximal exercise.


Figure 2.5 Energy contribution to total energy supply in maximal exercise (adapted from [80])
This information is more frequently presented in tabular form for maximal exercise lasting from 5 to 300 seconds as shown in Table 2.1.

Table 2.1 Estimates of anaerobic and aerobic energy contribution during selected period of maximal exercise (adapted from [80])

| Duration of exhaustive <br> exercise (sec) | \% Anaerobic | \% Aerobic |
| :---: | :---: | :---: |
| $0-10$ | 94 | 6 |
| $0-15$ | 88 | 12 |
| $0-20$ | 82 | 18 |
| $0-30$ | 73 | 27 |
| $0-45$ | 63 | 37 |
| $0-60$ | 55 | 45 |
| $0-75$ | 49 | 51 |
| $0-90$ | 44 | 56 |
| $0-120$ | 37 | 63 |
| $0-180$ | 27 | 73 |
| $0-240$ | 21 | 79 |

As mentioned in chapter 2.2.1, CP has been shown to be similar to the maximal lactate steady state power output, usually lasting 30 to 60 minutes, and it is at an intensity that separates heavy and severe exercise intensity domains. Table 2.2 shows that CP power output intensity elicits energy contribution primarily from aerobic glycolysis (roughly equivalent to the time it takes to perform $10,000 \mathrm{~m}$ run). The fuel source will be supplied by carbohydrate due to the fact that the aerobic breakdown of carbohydrate for energy occurs more rapidly than energy generated from fatty acid breakdown [81].

Table 2.2 Estimates of the percentage contribution of different fuels to ATP generation in various running events (adapted from [81])

| Event | Percent Contribution to ATP Generation |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | Glycogen |  |  | Blood Glucose | Triacylglycerol |
|  | Phosphocreatine | Anaerobic | Aerobic | (Liver Glycogen) | (Fatty Acids) |
| 100 m | 50 | 50 |  | - | - |
| 200 m | 25 | 65 | 10 | - | - |
| 400 m | 12.5 | 62.5 | 25 | - | - |
| 800 m | 6 | 50 | 44 | - | - |
| 1500 m | - | 25 | 75 | - | - |
| 5000 m | - | 12.5 | 87.5 | - | - |
| $10,000 \mathrm{~m}$ | - | 3 | 87 | 5 | 5 |
| Marathon | - | - | 75 | 5 | 20 |
| Ultramarathon (80 km) | - | - | 35 | 5 | 60 |
| 24 -h race |  | - | 10 | 2 | 88 |
| Soccer game | 10 | 70 | 20 | - | - |

There are several complex extensions of the original CP model that accurately predict performance and exhibit more precision compared to the original model. Morton showed that the residual sum of squares and root mean squares are significantly smaller for the modified model compared to the original model. However, investigators continue to revert to the original CP model for its simplicity.

There are several factors to be considered in modeling: (i) validity; (ii) reliability; (iii) sensitivity; (iv) practicability; and (v) usability. Three types of validity that can be applied to performance modeling, logical or face validity, criterion validity, and construct validity [82]. Face validity assesses whether a model estimates what it intends to estimate. Criterion validity allows for an objective measure of validity by correlating model estimates to criterion measures (concurrent validity) and/or subsequently predicts
performance (predictive validity) [83]. Lastly, construct validity refers to the degree in which a model could discriminate between groups [84]. Reliability is an important measure as it gives an indication of the variation of the model [85] and the factors affecting reliability can be categorized into test-specific factors (time to exhaustion or time trial, isokinetics or fixed load) and factors common to all tests (i.e. athletic status, gender, duration test time, mode of exercise). When choosing a model, it is important that the smallest worthwhile effect can be detected. It would be useful to have a quantitative measure of sensitivity or investigate the sensitivity of a protocol by comparing different interventions [29, 62, 69, 86]. Financial constraints (i.e. capital cost of equipment, operating costs,...) could be another important factor to be considered in validating a model with empirical data. Lastly, the ease of interpretation of data for knowledge transfer and application should be considered.

In this document, the model was developed from theoretical construct that has the ability to discriminate between groups while have the sensitivity to detect small changes. It provides estimates of the traditional parameters that can be readily interpreted and compared to other models.

### 2.3.1 Morton's 3-Parameter Model

Morton proposed one simple modification to the 2-parameter non-linear time-power model by introducing a new horizontal time asymptote, $k$, which is less than zero [20]. This means that the intersection of the hyperbola and power axis represents the maximum instantaneous power, $P_{\max }$, as shown in Figure 2.6. The proposed 3-parameter Critical Power model is represented in this form;

$$
\begin{equation*}
t=\frac{W^{\prime}}{P-C P}+\frac{W^{\prime}}{C P-P_{\max }} \tag{2.4}
\end{equation*}
$$



Figure 2.6 Morton's extension to CP model (adapted from [20])

### 2.3.2 Wilkie's Delayed Aerobic Supply Correction

Another modification to the 2-parameter CP model was proposed by Wilkie to account for the delay in aerobic supply [87], by introducing a correction factor for oxygen uptake kinetics [21]. A single exponential with time constant, $\tau$, is added to the original powertime Critical Power equation to represent the amount of energy released from anaerobic sources, before the attainment of an aerobic steady state at CP . This adjustment to the $\mathrm{W}^{\prime}$ is shown in Figure 2.7. However, Wilkie noted that this model does not fit well for extremely short durations or exercise lasting over 15 minutes. The proposed equation becomes:

$$
\begin{equation*}
P=\frac{W^{\prime}}{t}+C P \cdot t-C P \cdot \tau / t\left(1-e^{-\tau / t}\right) \tag{2.5}
\end{equation*}
$$



Figure 2.7 Wilkie's correction to CP model (modified from [88])

### 2.3.3 Péronnet and Thibault CP Model

A more complex extension has been proposed by Péronnet and Thibault [23, 89] that involves both kinetic delays in aerobic power supply and the progressive reduction of aerobic power that is able to be sustained for exercise durations over seven minutes in length [87, 90, 91]. The max power declines linearly in proportion to the natural logarithm of $t, \ln (t)$ for time in excess of seven minutes. The extension of the model takes the form:

$$
\begin{align*}
& P=\left[S / t\left(1-e^{-t / 20}\right)\right]+\frac{1}{t} \int_{0}^{t}\left[B M R+B\left(1-e^{-x / 30}\right)\right] d x  \tag{2.6}\\
& S=A \\
& B=M A P-B M R \\
& S=A+\left[A f \ln \left(T / T_{M A P}\right)\right] \\
& B=(M A P-B M R)+\left[E \ln \left(T / T_{M A P}\right)\right] \quad T>T_{M A P}
\end{align*}
$$

With $t$ and $x$ both measured in seconds; where S is the energy from anaerobic metabolism actually available to the individual, $A$ is the capacity of anaerobic metabolism, $B M R$ is the basal metabolic rate, $M A P$ is the maximum aerobic power, $T$ is the race duration, $T_{M A P}$ is the maximum duration of a race at maximum aerobic power ( $=7$ minutes), $f$ is the rate of decline of $S$ with $\ln T$ when $T>T_{M A P}(=-0.223)$.

### 2.3.4 Morton's 3-Energy Systems CP Model

Another complex extension to the CP model was proposed by Morton that comprises three energy systems, phosphagen utilization, anaerobic glycolysis and aerobic power [22,54]. Similar to models proposed by Wilkie and Péronnet, this model also involves kinetic delay in the aerobic energy supply. Like Péronnet's model, the maximum aerobic power declines progressively with longer durations, however, the difference is that the power output in Morton's model asymptotes to $84 \%$ of $\mathrm{VO}_{2 \max }$ which is a more realistic Critical Power output, rather than declining to zero as is the case in the Péronnet model. The model for a typical male subject is represented by the equation:

$$
\begin{equation*}
P=\frac{4.5+0.17 e^{-0.285 t}-3.333 e^{-0.00265 t}}{0.0216+0.00106 e^{-0.285 t}-0.0209 e^{-0.00265 t}} \tag{2.7}
\end{equation*}
$$

For $\mathrm{t}>6 \mathrm{~s}$. A Critical Power $(\mathrm{t} \rightarrow \infty)$ of 208 W is predicted and a maximally achievable power of 972 W for $\mathrm{t} \leq 6 \mathrm{~s}$. This model predicted results assume that the limitation to sustainable power is directly proportional to the glycogen store remaining [92]. An additional feature of the model is the inclusion of anaerobic threshold. Morton recognizes that exhaustion may occur before the anaerobic capacity is completely depleted as in the case of short duration exercise at intensity much above Critical Power may still contain significant reserves at the time of exhaustion [87].

### 2.3.5 3-min All-Out Test

Recently, attempts have been made to develop a protocol to estimate CP and $\mathrm{W}^{\prime}$ with a single test to avoid the time consuming testing protocol of CP model. Based on the assumption that the anaerobic capacity of an individual can be fully depleted during an all-out test, the power output at the end of the test should represent that power which is sustainable by the aerobic system alone, and this is the definition of Critical Power. The test must be long enough to deplete anaerobic stores and force energy production from aerobic sources [93]. Dekerle showed that with all-out exercise of approximately 90seconds in duration, power output at the end of exercise is still considerably higher than Critical Power [94]. Therefore, it is possible that in a longer all-out test, power output would continue to fall to an end-test power (EP) that would equal that associated with the Critical Power intensity. A 3-minute all-out test was proposed by Burnley showing that the EP is a good representation of the boundary between the heavy and severe exercise intensity domain [26]. Vanhatalo and colleagues observed in their sample population that EP was 287 W , which was not significantly different from, and highly correlated with, CP (287W; $\mathrm{p}=0.37 ; \mathrm{r}=0.99$ ). The standard error for the estimation of CP using EP was approximately 6 W . Similarly, the work completed above EP derived from the 3-min test $(15.0 \mathrm{~kJ})$ was not significantly different from, and correlated with $\mathrm{W}^{\prime}$, respectively (16.0 $\mathrm{kJ} ; \mathrm{p}=0.35 ; \mathrm{r}=0.84$ ) [27].

### 2.3.6 Critical Intensity

Up until this point, the relationships between work-time and power-time have been described extensively in exercises where power output measurement can be obtained easily, such as in cycling and rowing. The concept can be extended to all proxies for the intensity of exercise such as heart rate, force, speed, and other variables. In activities such as running and swimming, power output is difficult or impossible to measure. Hughson developed a model based on the work of Monod and Scherrer showing a similar inverse relationship between velocity and time to exhaustion that is defined by 2 parameters, critical speed (CS) and anaerobic distance capacity (ADC) [7], thus giving rise to the Critical Velocity (CV) model. CS is a measure of aerobic fitness that is related to gas exchange, metabolite, and performance thresholds [13, 45, 46, 52, 95, 96], while ADC is a measure of anaerobic capacity [97, 98]. By replacing the parameters CP and $\mathrm{W}^{\prime}$ in the original Critical Power equations (2.1-2.3) with the parameters CS and ADC, the Critical Velocity model can be written in these three mathematically equivalent forms, where $D$ is the total distance covered.

$$
\begin{gather*}
D=A D C+C S \cdot t  \tag{2.8}\\
S=\frac{A D C}{t}+C S  \tag{2.9}\\
t=\frac{A D C}{S-C S}
\end{gather*}
$$

### 2.3.7 Intermittent Efforts

The Critical Power concept has been adapted and used in interval training; a popular conditioning program which consisting of intervals of work and rest (active or passive) that are performed alternately. Different work/power-to-rest time intervals are employed as a means of training the various systems of energy transfer to lower blood lactate thresholds, and to increase the capacity for exercise as compared to the continuous
training protocol [99]. To apply the CP concept to intermittent exercise, it is necessary to separate work/power and time, in order to decipher between work and rest phases. Morton [100] proposed a model that accounts for the alternating cycle of a drain on the anaerobic capacity during work, followed by a partial refilling during rest, which is continued repeatedly until the anaerobic capacity is fully depleted. The time at which this occurs is the total endurance time, $t$, and, $n$, is the number of complete cycles (work and rest).

$$
\begin{equation*}
t=n\left(t_{w}+t_{r}\right)+\frac{W^{\prime}-n\left[\left(P_{w}-C P\right) t_{w}-\left(C P-P_{r}\right) t_{r}\right]}{P_{w}-C P} \tag{2.11}
\end{equation*}
$$

Where n is the number of cycles, $\mathrm{t}_{\mathrm{w}}$ is the work time, $\mathrm{t}_{\mathrm{r}}$ is the rest time, Pw is power output during the work phase, $\mathrm{P}_{\mathrm{r}}$ is the power output during the rest phase, and W ' and CP are the usual model parameters.

Chidnok et al. further extended this concept by examining the reconstitution of $\mathrm{W}^{\prime}$ at recovery periods in different exercise intensity domains. They observed the reconstitution of $\mathrm{W}^{\prime}$ increased more the lower the recovery intensity is below the CP level, or the longer the recovery duration at an intensity that is below CP [101]. CP and W' parameter estimates were significantly lower and higher, respectively, compared to the values derived from the original CP model. These results are similar to those of Morton and Billat [100].

Skiba also proposed a new mathematical framework to monitor the dynamic state of $\mathrm{W}^{\prime}$ during intermittent exercise (training and competition) [67]; where $W^{\prime}{ }^{\prime}{ }_{b a l}$ is the subject's known $W^{\prime}$ as calculated from the original CP model, $W_{\text {exp }}^{\prime}$ is the expended $W^{\prime},(t-\mu)$ is the time in seconds between segments of the exercise session that resulted in a depletion of $W^{\prime}$, and $\tau_{W^{\prime}}$ is the time constant of the reconstitution of the $W^{\prime}$.

$$
\begin{equation*}
W_{b a l}^{\prime}=W^{\prime}-\int_{0}^{t} W_{e x p}^{\prime} \cdot e^{-(t-\mu) / \tau \cdot W^{\prime}} \tag{2.12}
\end{equation*}
$$

### 2.4 Relationship Critical Power Model (Theoretical Framework)

In this section, the power-time relationship of the traditional CP model is revisited. More specifically the assumption of the linear relationship between work and time to exhaustion was investigated. Subsequently, a more generalized CP model will be proposed that has the freedom to describe the power-time relationship more closely which revealed a possible deviation from the traditional assumption based on an example of the theoretical CP models constructed from athletic type (sprint and endurance) and their respective muscle physiologies will be provided to support the relationship CP model.

### 2.4.1 Traditional CP model revisited

Monod and Scherrer first proposed the Critical Power model by observing a muscle being stimulated electrically, in order to lift different weights until exhaustion. A linear relationship was observed from fitting a regression line of the total work done and time to exhaustion. This is the first physiological model for human endurance [102] and is represented mathematically as,

$$
\begin{equation*}
W=W^{\prime}+C P \cdot t \tag{2.13}
\end{equation*}
$$

It can be rearranged to yield a mathematically equivalent model,

$$
\begin{equation*}
P=\frac{W^{\prime}}{t}+C P \tag{2.14}
\end{equation*}
$$

Graphical representation is shown in the figure below.


Figure 2.8 Power vs. time to exhaustion

Now assume a generic power-time graph with a curve similar to Figure 2.8, this relationship can be mathematically described in a general form as,

$$
\begin{equation*}
P=\frac{a}{t}+b \tag{2.15}
\end{equation*}
$$

Where a and b are parameter estimates, P is the average power output, and t is the time to exhaustion for each test session. The work-time relationship can be determined by integrating the power-time equation;

$$
\begin{equation*}
W=a \ln (t)+b t+c \tag{2.16}
\end{equation*}
$$

where $\mathrm{t} \neq 0$ and $c$ is an integration constant.

These theoretical equations, (2.15) and (2.16), bear a striking resemblance to the empirically-determined CP model equations, (2.13) and (2.14), with both sets of equations having a linear and a constant term except for the theoretical work equation (2.16) has an extra logarithmic term, $a \cdot \ln (t)$.

The linear term in the theoretical work equation (2.16), $b t$, is equivalent to the aerobic component of the work-time CP model equation (2.13) and the remaining two terms in
the theoretical work equation, $a \cdot \ln (t)$ and $c$, should sum up to be equivalent to the anaerobic component of the work-time CP model equation. A graphical illustration of the theoretical work model was constructed with arbitrary numbers selected for constants $\mathrm{a}, \mathrm{b}$, and c to meliorate the understanding of this concept. We can see that linear term, $b t$, has a dominating effect on the function as time increases since the logarithmic term increases at a slower rate (Figure 2.9).


Figure 2.9 Total Work vs. Time to Exhaustion (10 min)

At a quick glance at the figure, one would conclude that a linear relationship exists between total work done and time to exhaustion; however, upon careful investigation into the first minute of the time domain, a curvilinear relationship is revealed (Figure 2.10). The independent terms of equation (2.16) were plotted separately to better illustrate the effect that each has on the overall model.


Figure 2.10 Work vs. time to exhaustion (1 min)
This curvilinear relationship of $a \cdot \ln (t)$ would be impossible to capture with a few experimental points (regression line was fitted on four work-time points taken from the theoretical model, equation (2.16) and would be mistakenly seen as a linear relationship as shown in Figure 2.11.


Figure 2.11 Example of work-time relationship

The linear relationship observation would eventually lead to the incorrect interpretation that anaerobic work capacity has a fixed capacity, where in fact, the theoretical model showed the anaerobic terms is a continuous growing term with respect to time. Figure 2.12 depicts the difference in the anaerobic trend between both models (CP model is from
the equation in the above example, $\mathrm{y}=204.31$ time +4257.8 and theoretical model is from equation (2.16))


Figure 2.12 Anaerobic work for theoretical and CP model

### 2.4.2 Relationship model construct

Not only is the assumption of the linear relationship incorrect, but it has been assumed for all types of athletes (sprint or endurance). In other words, the model does not differentiate whether the relationship of power and time to exhaustion would be different between different types of athletes. Performance in sprint and endurance events has generally been attributed to the chemical energy input that fuels muscular contraction, and the force or power has been regarded as a dependent output [103, 104]. This concept has been used to explain the relationships between performance and duration of human exercise [105]. Numerous empirical data have supported the endurance portion of the curve well, but not the sprint [106], partly due to the inability to accurately measure the anaerobic chemical energy released during sprint efforts. This prompted an alternative analysis of sprinting performance by Bundle et al. [34]. Deviating from the traditional approach of the chemical energy input that cannot be measured, they focused on the mechanical output of the musculoskeletal system that can be measured. This force application model indicates a progressive impairment of skeletal muscle force
production, as a result of reliance on anaerobic metabolism to fuel intense sequential contractions, which can be seen on the sprint portion of the performance-duration curve (Figure 2.8). They also noted that the relationship between exercise mechanics, metabolism, and performance differs between sprint and endurance exercise [34]. A common relationship in the Critical Power model has traditionally been assumed to be generalized across all durations of performance efforts. In order to allow the model the freedom to describe the difference in relationship between types of athlete, a relationship constant, $n$, is introduced into the CP model.

$$
\begin{equation*}
P=\frac{\beta_{1}}{t^{n}}+\beta_{0} \tag{2.17}
\end{equation*}
$$

The shape of the power-duration curve would be defined by the relationship constant, n , and $\beta_{0}$ and $\beta_{1}$ are the parameter estimates of the relationship CP model. Some may confuse the relationship constant, n, with the traditional CP model "curvature constant", W', as referred to by several investigators [52, 97, 107-110]. As shown in equation (2.14), the product of a constant, $\mathrm{W}^{\prime}$, and a shape-defining inverse time term, $1 / \mathrm{t}$, indicates that W' simply amplifies the function without altering its shape. Therefore, the misleading curvature constant term required further clarification. However, the relationship constant, $n$, does indeed change the shape of the curve with all other parameters arbitrarily set as constants ( $\beta_{0}=200$ and $\beta_{1}=1000$ ). The smaller the relationship constant is, the less curvature (i.e. flatter the line) there is of the line and the longer it takes to reach asymptote (Figure 2.13). In other words, the curvature constant, n , describes the actual shape (i.e. sharpness) of the curve while $\mathrm{W}^{\prime}\left(\beta_{0}\right)$ amplifies (i.e. changes the size) and $\mathrm{CP}\left(\beta_{I}\right)$ changes the vertical position of the curve respectively.


Figure 2.13 Illustration of relationship constant

The parameter estimates have traditionally been estimated through fitting a line of best fit of the model through several exhaustive tests at various power intensities. $\beta_{0}$ is equivalent to $C P$ as defined by the Critical Power concept, however, it is less intuitive to conceptualize that $\beta_{1}$ is equivalent to $\mathrm{W}^{\prime}$, which is shown as the shaded area in Figure 2.14.


Figure 2.14 Power-time CP model

W' (area of the rectangle) at any given power output (P) and time ( t ) is the product of the sides,

$$
\begin{equation*}
W^{\prime}=(\mathrm{P}-C P) \cdot \mathrm{t} \tag{2.18}
\end{equation*}
$$

Substituting the relationship CP model fitted equation (2.17) into equation (2.18) gives us,

$$
\begin{equation*}
W^{\prime}=\left(\frac{\beta_{1}}{t^{n}}+C P-C P\right) t=\beta_{1} \cdot t^{1-n} \tag{2.19}
\end{equation*}
$$

In order to preserve the inverse curvature shape of the power-time curve, the relationship constant, $n$, always falls between 0 and 1 . Therefore $1-\mathrm{n}$ will always be between 0 and 1 , resulting in W' for the relationship CP model being an increasing root function. Hence, the anaerobic capacity increases with respect to time and is no longer a fixed constant as previously assumed. In order to estimate $W^{\prime}$ for the relationship CP model, we must define a duration (i.e. Time) for evaluation. Previous studies found that anaerobic capacity could be predicted from one all-out exercise test lasting 90-120 s [24, 25], therefore, 90 s could be used to estimate $\mathrm{W}^{\prime}$ for a relationship CP model.

### 2.4.3 Theoretical case study

A theoretical case study based on muscle fiber recruitment perspective should be able to demonstrate the difference between the power output versus time to exhaustion relationship of a sprinter from an endurance athlete. Henneman initially reported that there is a strong correlation between the size of a motor neuron and the activation order within a motor pool [111]. He observed that motor units were activated in order of increasing size, and this orderly recruitment of specific motor units to produce a smooth muscle action is known as the size principle [112]. The principle stipulates during muscle activation, and the motor units containing the smallest motor neurons fire first. As the activation signal increases, larger motor neurons are subsequently recruited and
activation strength increases. This orderly recruitment of motor neurons occurs in both increasing and decreasing activation levels. As activation level is increased, the smallest motor units fire first and are also the last to stop firing as the activation level decreases [113]. One key benefit from the size principle is that small neurons will be fired more regularly and for longer durations of time compared to larger neurons. The smaller motor units are typically more resistant to fatigue (Type I or slow twitch (ST) muscle fiber) [81].

Based on the work done by Bergh on muscle fiber composition in athletes for different sports (Figure 2.15), a basic expected athlete profile can be constructed from the muscle recruitment perspective and muscle fiber composition of the athlete type.


Sports

Figure 2.15 Muscle fiber composition in athletes representing different sports (modified from [114])

The average muscle fiber composition is shown in Figure 2.15 for different sports. The fast twitch (FT) fibers are further distributed nearly equally between type IIa (fast fatigue-resistant) and type IIb (fast fatigable) subdivisions [81]. This division is necessary as each type of muscle fiber's ability to resist fatigue differs [81]. The maximal force that can be developed per cross-sectional area of muscle tissue is constant across fiber types ( $\sim 25 \mathrm{~N} / \mathrm{cm}^{2}$ ) [115]. Therefore, the ability of different motor units to
develop active force is directly proportional to the number and diameter of fibers each motor unit contains [115]. ST fibers usually have less sarcomeres (smaller crosssectional area) than FT fibers, hence less force production [81]. The susceptibility to fatigue of a motor unit depends on the metabolic profile of its muscle fiber. ST fibers (smaller in size and innervation ratio) are recruited during sustained activity of moderate intensity and are highly resistant to fatigue. In contrast, the FT fibers are recruited during periods of high intensity activity [115].

A theoretical athlete power profile could be constructed based on the fiber composition, fiber activation profile, and fiber fatigue profile. Below are two theoretical examples of the extremes in the sport of running, long-distance running and 100 m sprints. The muscle composition for the long-distance runner is $63 \%$ ST fibers and $37 \%$ FT fibers (Figure 2.15). FT fibers can be further broken down into 19\% type IIa, 18\% type IIb ( $16 \%$ type IIx and $2 \%$ type IIb). The maximum force each fiber type can generate can be compared by normalizing against the ST fiber. The max force of FT fiber will be the ratio to the ST fiber. In our example, FT fibers are assumed to have the ability to generate a max force 1.25-1.75 times that of the ST fibers (arbitrary assumptions for demonstration only). Similar calculations can be done for the sprinter. Table 2.3 depicts the power profiles for both types of athlete.

Table 2.3 Power profile for endurance and sprint runners

| Fiber <br> Type | Resistance <br> to Fatigue | Fiber <br> Composition (\%) | Endurance <br> Relative <br> Force | Total <br> Force | Fiber <br> Composition (\%) | Sprint <br> Relative <br> Force | Total <br> Force |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| I | $>1 \mathrm{hr}$ | $63 \%$ | 1 | 63 | $43 \%$ | 1 | 43 |
| IIa | $<30 \mathrm{~min}$ | $19 \%$ | 1.25 | 23.75 | $28 \%$ | 1.25 | 35 |
| IIx | $<5 \mathrm{~min}$ | $16 \%$ | 1.5 | 24 | $25 \%$ | 1.5 | 37.5 |
| IIb | $<1 \mathrm{~min}$ | $2 \%$ | 1.75 | 3.5 | $4 \%$ | 1.75 | 7 |

Several exhaustive tests are required to construct a CP model. In this example, the duration of the tests are selected to progressively eliminate one type of fiber. Four exhaustive tests are performed with the force and time to exhaustion shown in Table 2.4. CP model outputs are then constructed from these tests, as shown in Figure 2.16.

Table 2.4 Sample tests for endurance and sprint runners

| Test Durations | Relative Force <br> (Endurance) | Relative Force <br> (Sprint) |
| :--- | :---: | :---: |
| 60 | 114.25 | 122.5 |
| 180 | 110.75 | 115.5 |
| 600 | 86.75 | 78 |
| 3600 | 63 | 43 |



Figure 2.16 Sample CP model for sprint and endurance runners

As shown in Figure 2.16, the relationship CP model (dashed lines) is able to capture the relationship between force and time to exhaustion for the endurance and sprint runners when compared to the traditional model (solid lines). Confirmation by empirical results remains elusive; hence the experiments proposed in the next section are designed in an attempt to verify the force application CP concept.

## 3 Studies Examining Critical Power Parameters and Protocols

### 3.1 Introduction

The traditional method of deriving CP and $\mathrm{W}^{\prime}$ is a time consuming process involving several exhaustive tests at various intensities. A 3-min all-out exercise test has been developed that yields estimates of CP and W ' for cycling, however, these models do not differentiate between types of athletes [26, 27]. Bundle's recent proposal on the demanddriven model of the performance-time relationship demonstrated a difference between the sprint and endurance athletes [34]. Therefore, we are proposing a more generalized model that has the freedom to describe the power-time relationship more accurately in order to demonstrate the difference between types of athlete.

$$
\begin{equation*}
P=\frac{\beta_{0}}{t^{n}}+\beta_{1} \tag{3.1}
\end{equation*}
$$

A common relationship has traditionally been assumed to generalize across all durations of performance efforts. In the Critical Power model, the relationship, $n$, between power output or work and time is generally assumed to be 1 for sprint and endurance athletes. My preliminary analysis [37] of the relationship between power and time to fatigue on university competitive rowers identified a significantly different relationship ( $\mathrm{n}=0.4$ ) from the traditional relationship $(\mathrm{n}=1)$. Thus the aims of the first study are to: (a) compare the relationship constant, $n$, to the traditional model relationship; (b) compare the relationship constant, $n$, of the sprint and endurance athletes; (c) identify if the relationship holds across sports with measurements taken with power and speed (i.e., cycling and swimming). We hypothesized that there would be a difference in the powertime relationship between sprint and endurance type athletes and that this relationship would be different from the currently assumed inverse relationship. Furthermore, we hypothesized the relationship pattern would also be consistent across cycling and swimming.

Stemming from the evidence that sprint athletes have higher anaerobic capacity and lower Critical Power/speed levels [36], the purpose of the second study is to determine the duration required to estimate the CP and W' from an all-out test for sprint and endurance athletes. It is hypothesized that the sprint athletes will take longer to expend W' and therefore to reach CP in an all-out exercise test compared to the endurance athletes. Gender differences in the time-duration all-out test will be investigated as well; however we hypothesize that no difference between genders will exist. Lastly, the aim of the third study is to develop a single test protocol that can accurately estimate CP parameters. The Constant-Power all-out test (CPT) addresses the drawbacks of the impractical lengthy nature of the Critical Power test and the physically and mentally exhaustive nature of the 3 MT .

### 3.2 Methods

### 3.2.1 Subject Characteristics

Competitive athletes ( 102 males and 67 females) in the sports of swimming, cycling, and triathlon were involved in the three studies (mean $\pm$ SD: age $28.3 \pm 12.0$ ). A total of 125 athletes (age range $=13-26$ years, group $=34$ sprinter and 88 endurance) were involved in the relationship CP model study, 72 cyclists and triathletes (age range $=19-65$ years, group $=20$ sprint and 52 endurance) volunteered for the shorter all-out duration test study, and 28 cyclists and triathletes (age range $=22-65$ years) participated in the Constant-Power all-out test study. Subjects' characteristics are shown in Table 3.1. Athletes were categorized into 2 types (sprint or endurance) based on national rankings for the swimmers and self-declaration for the cyclists. One of the advantages of using competition results is its ease of data collection which has been shown to be a viable protocol [116]. Athletes were included only if there were data for more than four race results in order to calculate the relationship constant. All swimming data were downloaded from the publicly accessible official Swimming Canada website (www.swimming.ca), therefore, informed consent was not obtained from athletes for the use of this information. For the cycling group, self-declaration of athletic types were verified with their race results, where sprinters generally place high in pack sprints in races while endurance trained cyclists tend to do better in tougher course races or race
performed at higher overall intensity. The cycling subjects were requested to refrain from participating in strenuous physical activity in the 24 h prior and to refrain from consuming caffeine and alcohol 3 h before reporting to the laboratory. They were informed about the study aims, the procedures and risks associated with the tests, and written and informed consent was obtained by all participants. The study was approved by the University of Toronto Review Ethics Board and was conducted in accordance with the Declaration of Helsinki.

Table 3.1 Characteristics of swimmers, cyclists, and triathletes (mean $\pm$ SD)

| Relationship CP Model |  |  |  |  |
| :--- | :---: | :---: | :---: | :---: |
|  | Cyclist/triathletes |  | swimmers |  |
|  | Females ( $\mathrm{n}=5$ ) | Males ( $\mathrm{n}=22$ ) | Females (n=51) | Males (n=46) |
| Age (yr) | $29.0 \pm 5.3$ | $38.9 \pm 11.0$ | $19.8 \pm 2.9$ | $20.2 \pm 2.4$ |
| Height (cm) | $180.6 \pm 8.0$ | $168.6 \pm 8.2$ |  |  |
| Body mass (kg) | $77.7 \pm 5.4$ | $57.6 \pm 5.0$ |  |  |
| Shorter All-Out Duration Test |  |  |  |  |
|  | Females (n=16) | Males (n=56) |  |  |
| Age (yr) | $35.4 \pm 9.7$ | $40.4 \pm 10.8$ |  |  |
| Height (cm) | $165.6 \pm 7.9$ | $177.7 \pm 15.7$ |  |  |
| Body mass (kg) | $58.1 \pm 5.3$ | $78.0 \pm 7.9$ |  |  |
| Constant-Power All-Out Test |  |  |  |  |
|  | Females (n=5) | Males (n=22) |  |  |
| Age (yr) | $29.0 \pm 5.3$ | $38.9 \pm 11.0$ |  |  |
| Height (cm) | $180.6 \pm 8.0$ | $168.6 \pm 8.2$ |  |  |
| Body mass (kg) | $77.7 \pm 5.4$ | $57.6 \pm 5.0$ |  |  |

### 3.2.2 Protocols

## Swimming

A database search was performed on the ranking of top 50 Canadian swim times for the 2013 season in freestyle for both male and female in the distances of $100 \mathrm{~m}, 800 \mathrm{~m}$, and 1500 m freestyle events, in order to represent extremes of the sport. Data were further screened for individuals having completed a minimum of four different race distances within a two-week period to avoid training effects when determining Critical Power parameters. There were no athletes ranked in the top 50 in both the short (i.e. 100 m ) and
the longer (i.e. 800 m and 1500 m ) distances to ensure a distinct classification of the extreme specialization of the sport.

## Cycling

Subjects were initially familiarized with all protocols and procedures. Subjects visited the laboratory on five occasions, with a minimum of 48 h of recovery between each test, and all tests were completed within 14 d . For each subject, only one exercise test was conducted on a given day, with each individual participating in no more than three experimental sessions in any given week. The subjects exercised on a computercontrolled, electromagnetically braked cycle ergometer in isokinetic mode (Excalibur Sport, Lode, Groningen, The Netherlands) with the cadence fixed at the subject's preferred racing cadence (range 85-105 rpm). Cadence is known to affect both end power in a 3-min all-out test and CP [16]. Since power is a product of both torque (force applied by the muscles) and angular velocity (cadence), it is difficult to determine if the decrease in power in an all-out test is due to force or cadence or both. Therefore, cadence is fixed in order to isolate the power that is generated from the muscle force.

In the first visit, an estimate of the subject's Critical Power (CP) and anaerobic work capacity ( $\mathrm{W}^{\prime}$ e) was determined using the three minute protocol of Vanhatalo and colleagues [27]. In the subsequent four visits, the subjects were randomly assigned to one of the four power outputs lasting between 1-10 min durations that resulted in exhaustion followed immediately by a non-disclosed duration all-out test.

Visit 1: 3-min all-out test. Before each trial, subjects performed their regular race warm up protocol lasting between $10-20 \mathrm{~min}$ and then $5-10 \mathrm{~min}$ of rest. The trial started with 1 min of easy cycling at $<100 \mathrm{~W}$. The subjects were asked to increase their effort during the last 5s of easy cycling which was followed by an all-out 3-min effort. The resistance to pedaling during the all-out effort was automatically adjusted by Lode ergometer based on the subject's pedaling effort to maintain cadence at the subject's preferred race cadence. Verbal encouragement was given throughout the tests, although neither elapsed time nor power feedback was given to the subjects during the test to avoid
pacing. Subjects were instructed and strongly encouraged to provide maximum effort at all times throughout the test. The end power (EP) was determined as the mean power output during the final 30 s of the test, and the $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$ is estimated as the power-time integral above the end power [27]. These parameters were used in equation (1.1) to determine the power outputs for the next successive four visits.

Visit 2-5: Constant-Power all-out tests. Each subject completed a randomized series of four Constant-Power all-out tests (CPT) to exhaustion, with each test implemented at a different power output chosen to result in exhaustion between 1-10 min. These tests were performed after the subject's preferred warm up. The subjects were asked to maintain the prescribed power output as consistently as possible at their preferred race cadence. The only feedback available to the subjects was the instantaneous power output to help maintain effort consistency. Once the subjects could no longer maintain the prescribed power output for more than 10 s , an all-out effort was instructed and power output feedback was removed until the termination of the test. Tests were terminated after power output fell to an asymptote which was sustained for two minutes (see Figure 3.1).

### 3.2.3 Data Analysis

There are several protocols and models being considered in the three studies. Table 3.2 outlined the parameter estimates that can be determined. All the parameter estimates for the different protocols and models will be presented in the results and discussion section.

Table 3.2 Parameter estimates can be determined from different protocols and models

| Models <br> Protocols | Traditional | Relationship | Morton's 3-parameter (post priori) |
| :---: | :---: | :---: | :---: |
| 3MT | WEP, EP | - | - |
| CPT (includes <br> traditional CP) | WEP, EP | CP, n, W' |  |
|  | CP, W' ${ }_{e}$ |  | CP, $\mathrm{P}_{\text {max }}, \mathrm{W}^{\prime}{ }_{\mathrm{e}}$ |

### 3.2.3.1 Relationship CP model

For some sports, such as running and swimming power output is difficult or impossible to measure, and therefore speed was implemented into the CP concept to develop the Critical Velocity (CV) model (Hughson 1984). The parameter estimates in the CV model
are similar to the CP model where critical speed (CS) is a measure of aerobic fitness, while anaerobic distance capacity is a measure of anaerobic capacity. Despite Hughson's observation of a similar inverse relationship as the CP model between speed and time to exhaustion, CV model parameter estimates cannot be compared to the parameter estimates determined from the CP model due to different measurements (power vs. speed). However, given that aerodynamic or hydrodynamic drag force $(F)$ can be described by the following equation [117]:

$$
\begin{equation*}
F=\frac{1}{2} \rho v^{2} C_{d} A \tag{3.2}
\end{equation*}
$$

where $\rho$ is the medium (air or water) density, $v$ is the velocity, $C_{d}$ is the drag coefficient, and $A$ is the cross-sectional area. Moreover, mechanical power $(P)$ is defined as [117]:

$$
\begin{equation*}
P=F \cdot v \tag{3.3}
\end{equation*}
$$

Thus the power required to overcome aerodynamic (cycling) or hydrodynamic (swimming) drag can be determined by substituting drag force (3.2) into power (3.3) as follows:

$$
\begin{equation*}
P=\frac{1}{2} \rho v^{3} C_{d} A \tag{3.4}
\end{equation*}
$$

It can be shown that power is proportional to the cube of the velocity of the air or water density, drag coefficient, and cross-sectional area, if all of these parameters were to be assumed as constants throughout the test duration.

$$
\begin{equation*}
P=k v^{3} \tag{3.5}
\end{equation*}
$$

Therefore, it would be possible to transform speed into power for those sports encountering great difficulties in measuring power output, and to be able to utilize the CP model.

The traditional approach in determining Critical Power parameters (W' and CP) is to calculate the parameters for each individual, and to compute the average for each parameter as the group mean. The CP parameters determined with this approach have been shown to be influenced by factors such as fitness level, age [78], number of tests [44], and duration of test [118-120]. Using a similar approach and applying the relationship CP model on each individual with 4 tests does not allow the model many degrees of freedom (1 DOF) to estimate 3 parameters (W', CP, n), which is essentially force-fitting the model to the data. Subsequently averaging the parameter estimates and presenting them as a group mean is thus highly dependent on the dominant factor(s) of the group. Therefore, in order to provide a more appropriate group estimation of the relationship of the CP model parameters (W', $\mathrm{CP}, \mathrm{n}$ ), one should consider using a mixed model (see below) with the entire set of data. It would also be necessary to normalize the data to account for the entire range of fitness abilities by expressing them as a ratio of their peak power (cycling) or 50 m swim time (swimming).

Data from swimming and cycling for both male and female were analyzed using a mixed nonlinear modeling procedure (PROC NLMIXED) in SAS (Version 9.4; SAS Institute, Cary, NC) to determine the relationship of power output and time to exhaustion between different types (sprint and endurance) of athletes. The nonlinear power-time CP statistical model consisted of fixed and mixed effects. The fixed effects were W' and CP, while the relationship constant, $n$, was set as a random effect to allow for variation around the mean. The difference in relationship constant between the two athletic groups is determined by setting one relationship constant as a variable and the difference in relationship constant between the groups as another variable. Since this difference has become a parameter of the model, the estimate for the difference and its p-value would allow us to reject the null hypothesis or to accept the alternative hypothesis. Statistical
testing of the relationship constant, $n$, was done against the traditional relationship ( $\mathrm{n}=1$ ) to identify if any deviation exists.

$$
\begin{equation*}
\text { power }=\frac{\beta_{1}+\beta_{2} I_{[t y p e=\text { sprint }]}}{\text { time }^{\left(\beta_{3}+\beta_{4} I_{[\text {type }=\text { sprint }]}+u\right)}}+\left(\beta_{0}+\beta_{5} I_{[\text {type }=\text { sprint }]}\right)+e \tag{3.6}
\end{equation*}
$$

Where
$B_{0}$ is an estimate for the critical power of endurance group
$\beta_{1}$ is an estimate for the endurance type used to calculate W' (refer to equation 2.19)
$\beta_{2}$ is an estimate that denotes change in $\beta_{1}$ from endurance to sprint type to be used to calculate W,
$\beta_{3}$ is an estimate for the relationship constant of the endurance group
$\beta_{4}$ is an estimate that denotes change in relationship constant from endurance to sprint type
$\beta_{5}$ is an estimate that denotes change in critical power from endurance to sprint type $u$ is the random effect on relationship constant for the subjects
$e$ is the random error of the model

Plots of residual versus predicted values from the analyses were examined for evidence of non-uniformity of error and appropriateness of the model.

### 3.2.3.2 Shorter duration all-out test

EP and W' were evaluated at every 15 s interval starting from 1 min to 3 min . EP is calculated as the average power output of the last 30 s of the test and $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$ is the sum integral of the power bounded by EP and the curve [26]. Consistency of the EP and W' for both groups at all the time intervals were compared to the 3MT EP using a two-way repeated-measures analysis of variance (ANOVA) mixed model in SAS (Version 9.4; SAS Institute, Cary, NC) with an unstructured assumption made on the variancecovariance parameter. The Dunnett-Hsu post-hoc procedure with multiple comparison control was used to control for type I error in making multiple comparisons, in order to determine the significant difference between the parameters estimated at each of the time intervals and to the parameters estimated at 3 min .

### 3.2.3.3 Constant-Power all-out test (CPT)

The traditional CP and W' were calculated from the duration for which the constant power was maintained for the four constant power tests. The EP was calculated as the average power output for the final 30 s of the test and W ' was estimated as the powertime integral above the EP. The EP from the 3MT was used as a reference EP for the four CPTs to determine the individual test W's. Two W's were extracted from each test: constant-power and unaccounted. Constant-power W' was the region bounded by the duration spent at maintaining constant power and EP, while unaccounted W' was bounded by the region immediately after the Constant-power region when power output gradually decreased to an asymptotic EP (Figure 3.1). Lastly, the total W' was the sum of constant-power and unaccounted W's.


Figure 3.1 Sample of 1 min test
Preliminary observation showed that several longer duration ( $>5 \mathrm{~min}$ ) test sessions resulted in subjects' average power outputs being lower than their 3MT EP, more specifically associated to subjects with a lower W'. The power output for longer durations determined from 3MT for subjects with small W' would only be slightly higher than CP (small W' over long time). Since the only feedback that is provided for the subject during the constant power test is the instantaneous power output, the fluctuation
of power output from second to second is large and therefore it is normal to have average power output for the test to be few watts higher or lower than prescribed. If the prescribed power output is slightly higher than CP then it would be possible the average EP be lower than 3MT EP resulting in a negative W' estimate which is incomprehensible. In addition, once the constant power can no longer be sustained, the subject would usually leveled off at an EP lower than the 3MT EP which would be unreasonable but analysis later would revealed this observation only happens in longer test durations. Therefore, an alternate approach was employed in calculating the constant-power W's by using the EP for the individual test.

Comparisons of the EP, constant-power W', unaccounted W', and complete W' between all the tests was made using a one-way repeated-measures analysis of variance (ANOVA) mixed model in SAS (Version 9.4; SAS Institute, Cary, NC) with the compounded symmetry assumption made on the variance-covariance parameter. Dunnett-Hsu posthoc procedure with multiple comparison control was used to control for type I error in multiple comparisons, in order to determine the significant difference between the parameters determined from all the tests and to the parameters estimated from the CP model.

### 3.3 Results and Discussion

### 3.3.1 Relationship CP Model

### 3.3.1.1 Results

The parameter estimates ( $\mathrm{W}^{\prime}$ e, $\mathrm{CP} / \mathrm{CS}$, and n ) for different transformed CP models (standardized power, standardized speed, power, and speed) are reported in Table 3.3. Significant differences were not observed for the power-time relationship between the sprint and endurance group in cycling and swimming, however, all of the relationship constants were significantly different from the traditional model relationship, $n=1$.

Table 3.3 $\mathbf{W}^{\prime}{ }_{\mathrm{e}}, \mathrm{CP} / \mathbf{C S}$, and $\mathbf{n}$ for different transformed models (mean $\pm$ SEE)

|  |  | Sprint |  |  | Endurance |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | W'e | n | CP/CS | W'e | n | CP/CS |
| Swimming | Power ratio | $68.75 \pm 0.29$ | $0.29 \pm 0.07$ | $\mathbf{- 0 . 1 1 \pm 0 . 1 3}$ | 47.14* $\pm 0.11$ | 0.29* $\pm 0.03$ | 0.23* $\pm 0.04$ |
|  | Power | $251 \pm 6 \mathrm{~J}$ | $0.59 \pm 0.09$ | $2.40 \pm 0.38 \mathrm{~W}$ | 185* $\pm 2 \mathrm{~J}$ | $0.53 * \pm 0.03$ | $2.82 * \pm 0.12 \mathrm{~W}$ |
|  | Speed ratio | $64.24 \pm 0.12$ | $0.14 \pm 0.05$ | $0.15 \pm 0.18$ | 37.41* $\pm 0.04$ | $0.14 * \pm 0.03$ | 0.49* $\pm 0.07$ |
|  | Speed | $53.52 \pm 0.18 \mathrm{~m}$ | $0.32 \pm 0.07$ | $1.14 \pm 0.10 \mathrm{~m} / \mathrm{s}$ | 36.50* $\pm 0.06 \mathrm{~m}$ | $0.30 * \pm 0.03$ | $1.30 * \pm 0.03 \mathrm{~m} / \mathrm{s}$ |
|  |  | W'e | n | CP | W'e | n | CP |
| Cycling | Power ratio | $\mathbf{1 7 . 5 7} \pm \mathbf{0 . 7 2}$ | $0.29 \pm 0.06$ | $0.08 \pm 0.04$ | 18.35* $\pm 0.17$ | $0.41 * \pm 0.13$ | 0.16* $\pm 0.08$ |
|  | Power | $17072 \pm 160 \mathrm{~J}$ | $0.44 \pm 0.07$ | $158 \pm 36 \mathrm{~W}$ | $16443 * \pm 376 \mathrm{~J}$ | $0.48 * \pm 0.15$ | 215* $\pm 73 \mathrm{~W}$ |

bold = parameter estimates are significantly different between sprint and endurance

Upon glancing at the parameter estimates determined from the swimming power model, they appeared to be orders of magnitude lower than the same parameters determined from the cycling power model. The reason may be linked to the calculation of transformed power (3.5), the proportionality constant, k , which includes the drag coefficient, water density, and frontal surface area of the swimmer, which was not calculated because of lack of individual swimmer data and therefore was left as a constant variable. A "better" representation of the power output should have included the factor k in the result, however the factor k would be cancelled out when back-transformed as power into speed as shown in Table 3.4.

There was an unusual observation (Table 3.3) in the standardized CP model for swimming where the critical speed showed a negative value ( $\mathrm{CS}=-0.90 \mathrm{~m} / \mathrm{s}$ ). This value eludes interpretation and may be explained by all of the swim test durations being less than 5 minutes for the sprint group, which was a deviation from the recommendation of 2 to 15 minutes [121]. Failing to have tests of longer duration for the sprint group in the swimming study limits the model to describing only the initial steep power decrease segment of the power-time curve and the inability for the curve to reach a proper asymptote to accurately estimate CS (Figure 3.2). In contrast, Figure 3.3 shows tests performed across a range of recommended test durations for the endurance swimmers and for the cyclists in the cycling study. Distinct asymptotes can be clearly identified to properly describe the Critical Power for the sprint and endurance cycling groups.

Therefore, the range of test duration remains as one of the limitations of the CP model,
and the effects are even more pronounced for the relationship CP model as the curve is fitted more closely to the data.

Standardized critical speed, Critical Power, and standardized Critical Power were backtransformed to speed for swimming and all of the models showed a significant difference in speed between the sprint and endurance groups (speed $p=0.02$, standardized speed $p=$ 0.003 , standardized power $p=0.0007$ ), except for the transformed power model ( $p=$ 0.12 ) as shown in Table 3.4. Similarly in cycling, significant differences in backtransformed powers were observed only in the standardized power model ( $\mathrm{p}=0.046$ ), but not in the power model $(\mathrm{p}=0.22)$. A consistent trend of higher critical speeds and powers was observed for the endurance group compared to the sprint group in all of the transformed models (shown in Figure 3.2 and Figure 3.3).

Estimates of ${ }^{\prime}{ }^{\prime}{ }_{\mathrm{e}}$ for all of the models showed a significant difference ( $\mathrm{p}<0.0001$ ) between types of athlete, except for the Critical Power model for cycling ( $\mathrm{p}=0.064$ ). The W' ${ }_{\mathrm{e}} \mathrm{s}$ from all of the standardized models was significantly higher than its respective non-standardized model.

Table 3.4 Back-transformed $W^{\prime}$ and CP/CS (mean $\pm$ SEE)

|  |  | Sprint |  | Endurance |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | W'e | CS | W'e | CS |
| Swimming | Power ratio | $467 \pm 2 \mathrm{~J}$ | $-0.90 \pm 0.96 * * \mathrm{~m} / \mathrm{s}$ | $320 \pm 1 \mathrm{~J}$ | $1.16 \pm 0.65 * * \mathrm{~m} / \mathrm{s}$ |
|  | Power | $250 \pm 6 \mathrm{~J}$ | $1.34 \pm 0.72 \mathrm{~m} / \mathrm{s}$ | $185 \pm 7 \mathrm{~J}$ | $1.41 \pm 0.49 \mathrm{~m} / \mathrm{s}$ |
|  | Speed ratio | $121.66 \pm 0.23 \mathrm{~m}$ | $0.66 \pm 0.34 * * \mathrm{~m} / \mathrm{s}$ | $70.84 \pm 0.08 \mathrm{~m}$ | $0.98 \pm 0.13 * * \mathrm{~m} / \mathrm{s}$ |
|  | Speed | $53.52 \pm 0.18 \mathrm{~m}$ | $1.14 \pm 0.10 * \mathrm{~m} / \mathrm{s}$ | $36.50 \pm 0.06 \mathrm{~m}$ | $1.30 \pm 0.03 * \mathrm{~m} / \mathrm{s}$ |
|  | Traditional CV | $11.84 \pm 3.07 \mathrm{~m}$ | $1.57 \pm 0.11 \mathrm{~m} / \mathrm{s}$ | $9.30 \pm 2.10 \mathrm{~m}$ | $1.55 \pm 0.08 \mathrm{~m} / \mathrm{s}$ |
|  |  | W'e | CP | W'e | CP |
| Cycling | Power ratio | $21544 \pm 882 \mathrm{~J}$ | $113 \pm 49 *$ W | $22495 \pm 208 \mathrm{~J}$ | 183 $\pm 98 *$ W |
|  | Power | $17072 \pm 160 \mathrm{~J}$ | $158 \pm 36 \mathrm{~W}$ | $16443 \pm 376 \mathrm{~J}$ | $215 \pm 73 \mathrm{~W}$ |
|  | Traditional CP | $9015 \pm 3829 \mathrm{~J}$ | $265 \pm 69 \mathrm{~W}$ | $9186 \pm 4897 \mathrm{~J}$ | $299 \pm 47 \mathrm{~W}$ |
|  | 3 min all-out | $16813 \pm 4334 \mathrm{~J}$ | $234 \pm 62 \mathrm{~W}$ | $14655 \pm 4497 \mathrm{~J}$ | $287 \pm 42 \mathrm{~W}$ |
| * $\mathrm{p}<0.05$ |  |  |  |  |  |
| ** $\mathrm{p}<0.001$ |  |  |  |  |  |



Figure 3.2 Standardized-power relationship CP model for swimmers


Figure 3.3 Standardized relationship CP model for cyclists

### 3.3.1.2 Discussion

These results suggest that the relationship between intensity and duration is significantly different from the traditional assumption of an inverse relationship by the Critical Power model. We found that the fitted exponent parameter n is significantly less than the assumed value of 1.0 in the traditional model. This observation indicates that $\mathrm{W}^{\prime}$ is not constant, but rather that the decline in power with time is more gradual than traditionally assumed. We observed no significant difference in the power-time relationship between sprint and endurance athletes, more specifically in swimmers and cyclists.

The relationship constant showed no differences between the two groups in all of the models, however when compared to the traditional model, there is strong evidence ( $\mathrm{p}<$ 0.001 ) suggesting that the relationship constant is different from the previously assumed inverse relationship of $\mathrm{n}=1$. The interaction between sport and athletic group showed a significant difference ( $p=0.014$ ), however upon further analysis, the result showed no difference in relationship constant within the sport (cycling $\mathrm{p}=.1068$ swimming $\mathrm{p}=0.8724$ ) but differed between sports ( $\mathrm{p}<0.001$ ). The relationship constant of 0.40 for the cyclists is consistent with our preliminary analysis [37] of the relationship between power and time to fatigue in university competitive rowers. The lower value of the relationship constant ( $\mathrm{n}=0.29$ ) for the swimmers can partly be attributed to the differences in drag force (hydrodynamics for swimming and aerodynamics for cycling) and possibly in training volume for the different levels of athletes taking part in the comparison. Training volume has been shown to increase as the level of performer increases, mostly through training frequency in sports like running and cross-country skiing, but also through increases in average session duration, particularly in cycling [122]. A typical yearly training volume for champion athletes in the sports of swimming, rowing, and cycling are in the range of 1100-1300 hours [122], so logically there would be a lower training volume for athletes at the non-elite level. The swimmers in the present study were nationally ranked while the cyclists and rowers were competing at the club and university level respectively. Participation in endurance training causes muscular adaptations and leads to improved capacity for oxygen exchange between capillary and tissue [123, 124], improved control of metabolism within the muscle fibers including a
greater rate of fatty acid oxidation [38] and attenuating the metabolic signals to reduce rate of carbohydrate breakdown [39]. This occurs in slow and fast twitch fibers leading to increased fatigue resistance. Another effect of endurance training is the conversion of Type II (fast-twitch) fiber characteristics to type I (slow-twitch) fibers [40]. The percentage of type I fibers increases with various type of endurance training protocols such as cycling ( $+12 \%$ type I) and long distance running (+17\% type I) [125].

Observations also suggested that intense endurance training could alter the fiber gene profile and transform type IIb into type IIa fibers, and of type IIa into type I fibers [126, 127]. Therefore, endurance training volume and intensity may have an effect on the shape of the power-time relationship with higher volume contributing to fiber type shifting resulted in a more subtle decrease (smaller n) in performance with respect to time.

Given that Morton's 3-parameter model in the power-time form (derived from equation 2.4) has a similar power-time relationship curve; a comparison was made between the three models (Figure 3.4).


Figure 3.4 CP models comparison (Traditional, Morton's 3-parameter, Relationship)

The CP estimate was the lowest with the relationship model (16\%) when compared to both Morton's 3-parameter ( $25 \%$ ) and the traditional CP model (27\%), while W' ${ }_{\mathrm{e}}$ showed an opposite trend with relationship model had the highest estimate of 15.65 , followed by Morton's 3-parameter model with 8.40 and traditional CP model with 4.33. The comparison of the "shape" of the 3-parameter model was less straightforward as it was for the traditional and relationship model (comparing relationship constant $n$ ), a visual comparison of the shape of the curve showed that 3-parameter model was the most gradual of the 3 models as evidence from Figure 3.5. Since maximum likelihood estimation was used to estimate the parameters of the models and the three models are not nested, the Akaike's information criterion (AIC) was used to assess the goodness of fit of the models. Relationship and Morton's 3-parameter model showed a better fit than the traditional CP model (the smaller the AIC, the better. Tradition = -280 , AIC Morton $=-319$, AIC Relationship $=378$ )


Figure 3.5 CP Models comparison on time 0-200s

Parameter estimates for different transformed models are presented in Table 3.3 and Table 3.4. For sports in which it is difficult to measure power output, such as swimming, it is possible to transform speed into power in order to use the CP model (3.4).
Moreover, standardizing the data relative to peak output to account for the range in power outputs and employing a mixed statistical model with more degrees of freedom (i.e. higher power) allowed for a more accurate estimate of the group parameter means.

The results in Table 3.3 and
Table 3.4 indicate that the relationship constants ( n ) between the sprint and endurance groups were not different in swimmers and cyclists. However, the W' and CP/CS were significantly different for the different types of athletes. Specifically, higher W' ${ }_{\mathrm{e}}$ and lower CP/CS was observed for the sprint group when compared to the endurance group for all models, except for the traditional model and the cycling power model. This can likely be attributed to the difference in the number of subjects in each group, i.e. sprint = 8 , endurance $=19$. Our findings are consistent with those of Gollnick et al., who have similarly observed that endurance-trained athletes can perform at high rates for longer durations of time, while sprint-trained athletes demonstrate superior anaerobic performance on high intensity, short duration exercises have been identified [35]. These findings further corroborate the observation noted by Bundle that the performance relationship differs between sprint and endurance exercises [34].

Our results showed no differences (swimming $p=0.24$, cycling $p=0.23$ ) in the means of CS between sprint and endurance groups with the traditional model which is supported by similar findings in young swimmers by Zacca [128]. One possible explanation for the inability to detect significant differences may be due to lack of power or degrees of freedom (2 DOF in our study, 4 DOF in Zacca study) using the traditional method to calculate group CS/CP parameters. Further analysis using the mixed model on the swim data wherein the CS estimations were calculated with 94 DOF resulted in high enough power to detect a significant difference between the two groups $(p=0.001)$. The increased power of the mixed model analysis used in our study could potentially be beneficial for intervention and treatment studies that have failed to detect significant effects using the traditional analysis method.

There was an unusual observation (Table 3.3) in the standardized CP model for swimming where the critical speed showed a negative value ( $\mathrm{CS}=-0.90 \mathrm{~m} / \mathrm{s}$ ). This value eludes interpretation and may be explained by all of the swim test durations being less than 5 minutes for the sprint group, which was a deviation from the recommendation of 2
to 15 minutes [121]. Failing to have tests of longer duration for the sprint group in the swimming study limits the model to describing only the initial steep power decrease segment of the power-time curve and the inability for the curve to reach a proper asymptote to accurately estimate CS (Figure 3.2). In contrast, Figure 3.3 shows tests performed across a range of recommended test durations for the endurance swimmers and for the cyclists in the cycling study. Distinct asymptotes can be clearly identified to properly describe the Critical Power for the sprint and endurance cycling groups. Therefore, the range of test durations remains as one of the limitations of the CP model, and the effects are even more pronounced for the relationship CP model as the curve is fitted more closely to the data.

Standardized CP model in both cycling and swimming showed a much lower $\mathrm{CP} / \mathrm{CS}$ compared to the traditional (Swimming endurance $75 \%$, cycling sprint $43 \%$, cycling endurance $61 \%$ ) and 3MT values (cycling sprint $48 \%$, cycling endurance $64 \%$ ). It has been established that CP or 3 MT is the demarcation between heavy to severe exercise intensity domain [26,27] while the blood lactate threshold was identified as the demarcation between moderate to heavy exercise intensity domain [13, 129]. An estimate of the lactate threshold domain was observed at $76 \%$ of EP with the range of confidence interval from $56 \%$ to $97 \%$ [31]. The CP/CS estimates for the endurance group appeared to be within the lactate threshold domain range but were not the case for the sprint group. Therefore, the lower CP/CS values estimated by standardized CP model may in fact be defining a domain that is correlated to the lactate threshold domain which is more consistent with the definition of Critical Power as theoretical power output that one could maintain indefinitely [4] however, in practice the CP have been shown to be sustained for approximately $30 \mathrm{~min}[18,42,48,51]$.

W' ${ }_{\mathrm{e}}$ is higher in standardized power model than the traditional CP model for swimming and cycling in both groups. The difference in W' ${ }^{\prime}$ probably could be explained partially by the inaccuracy in the constant work-rate protocol of the traditional CP model in capturing the total work done. $\mathrm{W}^{\prime}$ e may not be completely depleted at the termination (i.e. inability to maintain constant power output) of the Constant-Power all-out test [19].

If exercise was to continue after the termination of the test, power output would decrease but still be above CP until at some point in time the power output would asymptote to or below CP (Tsai, unpublished data). This additional energy expenditure is not accounted for in the traditional CP model which results in an underestimate of the total ${ }^{W}$ ' ${ }_{\mathrm{e}}$ for a single exhaustive test. Total effects of unaccounted ${ }^{\prime}$ ' ${ }_{\mathrm{e}}$ from 3-4 exhaustive tests as required by CP model [121] could alter the estimation of the CP parameters.

### 3.3.2 Shorter Duration All-Out Test

### 3.3.2.1 Results

EP and W' ${ }^{\mathrm{e}}$ for sprint and endurance groups for all the time intervals are reported in Table 3.5. Significant difference in EP was not observed for time intervals beyond 120 s for both endurance and sprint groups and a similar pattern was observed for $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$ (Figure 3.6). The delta EP and delta $W^{\prime}$ e (difference in EP and $W^{\prime}$ e from 3MT EP) appeared to be higher for the endurance than the sprint group. However further analysis showed there is no difference between both groups at every time interval (EP p-value ranged from 0.3476 to 0.8286 and W' ${ }_{\mathrm{e}}$ p-value equals 1 for all). A consistent pattern of higher EP and lower $W^{\prime}$ e was observed for the endurance group than the sprint group in all time intervals.

Table 3.5 EP and $\mathbf{W}^{\prime}{ }_{\mathrm{e}}$ at each time interval for sprint and endurance group (mean $\pm$ SEE)

| Endurance |  |  | Sprint |  |
| :---: | :---: | :---: | :---: | :---: |
| Time (s) | EP (W) | $\mathbf{W}^{\prime}{ }_{\mathrm{e}} \mathbf{( J )}$ | $\mathbf{E P}(\mathbf{W})$ | $\mathbf{W}_{\mathrm{e}(\mathbf{~} \mathbf{( J )}}$ |
| 60 | $349 \pm 10$ | $8440 \pm 456$ | $308 \pm 17$ | $9598 \pm 742$ |
| 75 | $302 \pm 9$ | $11033 \pm 522$ | $254 \pm 15$ | $12649 \pm 849$ |
| 90 | $284 \pm 9$ | $12353 \pm 558$ | $239 \pm 14$ | $13757 \pm 908$ |
| 105 | $276 \pm 9$ | $12990 \pm 572$ | $237 \pm 14$ | $13947 \pm 931$ |
| 120 | $270 \pm 8$ | $13592 \pm 571$ | $236 \pm 13$ | $14071 \pm 929$ |
| 135 | $267 \pm 8$ | $13961 \pm 589$ | $232 \pm 13$ | $14435 \pm 959$ |
| 150 | $264 \pm 8$ | $14250 \pm 632$ | $227 \pm 13$ | $15053 \pm 1030$ |
| 165 | $263 \pm 8$ | $14479 \pm 658$ | $224 \pm 13$ | $15578 \pm 1072$ |
| 180 | $260 \pm 8$ | $14819 \pm 701$ | $223 \pm 13$ | $15695 \pm 1141$ |



Figure 3.6 Differences in EP and $W^{\prime}$ e from 3 MT between athlete types
EP and ${ }^{\prime}$ ' ${ }_{\mathrm{e}}$ for all the time intervals for both genders are reported in Table 3.6. Significant differences in EP were not observed for time intervals beyond 120 s for females and 135 s for males (Figure 3.7). There were no differences in $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$ after 105 s for females and 135 s for males. A similar decreasing trend was observed for the mean difference in EP and ${ }^{\prime}$ ' ${ }_{\mathrm{e}}$ for both genders, in response to the time interval increasing with males showing higher differences in both parameters compared to females. Further analysis unveiled that there are significant differences between genders at every interval (both EP and W' p-value less than 0.001). Lastly, higher EP and W' ${ }^{\text {e }}$ values were observed in males compared to the females for all of the time intervals.

Table 3.6 EP and $W^{\prime}{ }_{\mathrm{e}}$ at each time interval between sex (mean $\pm$ SEE)

|  | Female |  | Male |  |
| :---: | :---: | :---: | :---: | :---: |
| Time (s) | $\mathbf{E P}(\mathbf{W})$ | $\mathbf{W}^{\prime} \mathbf{e}_{\mathrm{e}} \mathbf{( J )}$ | $\mathbf{E P} \mathbf{( W )}$ | $\mathbf{W}^{\prime}{ }_{\mathrm{e} ~(J)}$ |
| 60 | $251 \pm 15$ | $5777 \pm 738$ | $362 \pm 8$ | $9593 \pm 391$ |
| 75 | $218 \pm 14$ | $7689 \pm 822$ | $309 \pm 8$ | $12539 \pm 436$ |
| 90 | $209 \pm 14$ | $8256 \pm 833$ | $289 \pm 7$ | $13996 \pm 442$ |
| 105 | $204 \pm 14$ | $8689 \pm 849$ | $282 \pm 7$ | $14533 \pm 450$ |
| 120 | $202 \pm 13$ | $8876 \pm 811$ | $277 \pm 7$ | $15084 \pm 430$ |
| 135 | $198 \pm 13$ | $9305 \pm 859$ | $274 \pm 7$ | $15435 \pm 455$ |
| 150 | $193 \pm 13$ | $9985 \pm 985$ | $271 \pm 7$ | $15729 \pm 522$ |
| 165 | $191 \pm 13$ | $10270 \pm 1041$ | $269 \pm 7$ | $16046 \pm 552$ |
| 180 | $191 \pm 13$ | $10321 \pm 1108$ | $267 \pm 7$ | $16389 \pm 588$ |



Figure 3.7 Differences in EP and ${ }^{\prime}{ }^{\prime}$ e from 3MT between sex

### 3.3.2.2 Discussion

The results presented suggest that an all-out test duration of 135 s provides accurate estimate of the $3 \mathrm{MT} \mathrm{W}^{\prime}{ }_{\mathrm{e}}$ (sprint $\mathrm{p}=0.1146$, endurance $\mathrm{p}=0.1607$ ) and CP (sprint $\mathrm{p}=0.1029$, endurance $\mathrm{p}=0.1424$ ) for both groups of athletes. However, after adjusting for weight differences between the sexes in the post priori analysis, the duration of 150 s was shown to sufficient duration for the all-out test.

EP and W' ${ }^{\prime}$ did not show significant differences from 3MT at time intervals beyond 135 s for both athlete groups. The results indicate that both sprint and endurance athletes do not have to complete the entire 3 min duration as required by the traditional 3 MT to determine values for ${ }^{\prime}{ }^{\prime}$ e and EP. The test durations can be significantly reduced by $25 \%$ and still produce parameter estimates that differ by less than $2 \%$ from the 3 MT values. The endurance group showed an asymptote to CP and it was higher compared to its counterpart, however, the opposite was observed for $W^{\prime}$ ' ${ }_{e}$, with a higher value obtained in the sprint group compared to the endurance group. This is consistent with similar observations reported by other investigators [35, 36].

An initial analysis showed that the mean values for EP and ${ }^{\prime}$ 'e at each time interval were dependent on sex, (EP p $=0.0009, W^{\prime}{ }_{e} p=0.0003$ ) or the type of athlete ( $E P \mathrm{p}=0.0341$, W'e $\mathrm{p}=0.0302$ ) independently of each other, despite the logical assumption that the parameter estimates would be dependent on both factors. However upon further investigation, there is no evidence that the mean values for EP and W'e are dependent on sex and athlete type $(p=0.5884)$.

Our results could be confounded by the fact that greater than $80 \%$ of female EP values in our study were in the bottom third range of EPs. In order to eliminate the unbalanced concentration of females, a sample from the bottom third of the dataset was reanalyzed with the sample size ( $\mathrm{n}=13$ each) for sex and end power (male $193 \pm 26 \mathrm{~W}$, female $171 \pm 36 \mathrm{~W})$ matched. The analysis indicated 105 s to suffice as a minimum duration for both sexes to accurately estimate CP parameters. This provides a cogent argument that the time interval to estimate CP parameters is not dependent on sex, but rather that it may be more related to power output range.

In a more in-depth investigation of the test duration dependency on power output, the subjects were separated evenly $(\mathrm{n}=24)$ into three categories based on their EP ranking (low $180 \pm 30 \mathrm{~W}$, med $255 \pm 17 \mathrm{~W}$, high $313 \pm 19 \mathrm{~W}$ ) and a weak relationship ( $\mathrm{p}=0.106$ ) was revealed. Low and high groups showed that a time duration of 105 s was sufficient and for the med group, a time duration of 150 s would be required to accurately estimate CP parameters. The shorter time interval for the high EP group (all male, sprint $\mathrm{n}=3$, endurance $\mathrm{n}=21$ ) indicates that the athletes are well endurance-trained with the ability to maintain high rates as previously observed [35, 36]. In contrast to the high EP group, longer time interval appears to be required for the medium group ( 4 females, 20 males, sprint $\mathrm{n}=7$, endurance $\mathrm{n}=17$ ) demonstrating that the less well-trained athletes display a more gradual leveling off to EP. Lastly, the results from the low EP group ( 12 male, 12 female, sprint $n=10$, endurance $n=14$ ) showed shorter time to exhaustion for the recreationally trained athletes therefore suggesting that a short time duration for an all-out test would be sufficient. However, it would be difficult to make a general
recommendation regarding the time duration for the all-out test, due to the presence of mixed gender in the low EP group that may have had a wide range of fitness levels. The females in the higher end of the low EP group may be considered as relatively well trained, but are mistakenly categorized as less fit under the male dominant EP scale. The nine well-trained females in the low group could confound analysis and therefore it is not surprising that similar trends were observed in the low group and high (well-trained) groups.

Furthermore, there is large variance evident in the EPs for the low EP group compared to the other groups. Therefore, pooling a homogenous subset of male only data (low $\mathrm{n}=19$, sprint $=9$, endurance $=9, E P=207 \pm 30 \mathrm{~W}$, med $\mathrm{n}=19$, sprint $=4$, endurance $=4, \mathrm{EP}=$ $274 \pm 15 \mathrm{~W}$, high $\mathrm{n}=18$ sprint $=3$ endurance $=3 \mathrm{EP}=320 \pm 16 \mathrm{~W}$ ) could eliminate the mixed fitness levels, and more accurately reveal the time interval dependency on power output if any. The results showed no effect of fitness level (i.e. low, med, and high power output) on time intervals on estimating CP parameters ( $p=0.339$ ).

Cycling time to exhaustion was highly correlated with lean body mass $(\mathrm{r}=0.84)$ and thigh total and lean volume displayed weaker correlations with time to exhaustion ( $\mathrm{r}=$ 0.66 and $r=0.73$, respectively) indicating that body mass can be a confounding variable to cycling performance [130]. Similar observations in our analysis showed body mass ( $\mathrm{p}=0.0001$ ) contributed significantly to explaining the variance in EP and W' in the allout test, while age $(\mathrm{p}=0.4665)$ and height $(\mathrm{p}=0.245)$ did not. In other words, bigger (or heavier) athletes would generate more power in general because of more muscle mass, accounting for differences in body composition. This marked advantage is partially due to the known relationship of surface area to mass being inversely proportional to the indices of size cycling on the road [131]. In a controlled laboratory setting where aerodynamic drag is a non-factor, the large cyclists would have a considerable advantage. Relative EP (similar to relative $\mathrm{VO}_{2}$ ), expressing EPs as a ratio of their weight, allows one to compare values between people of different sizes. Despite the result of absolute EP suggesting a time difference between gender (female 120 s , male 150 s ), the relative

EP showed no differences in time duration between the gender, and both groups appear to require 150 s of all-out testing to accurately estimate CP parameters.

### 3.3.3 Constant-Power All-Out Test

### 3.3.3.1 Results

The mean and standard deviation values of all the calculated variables for each test are reported in Table 3.7Table 3.6. Significant differences were observed between the all-out test EPs and CP. Significant differences were detected only for CPT durations $>3$ min when compared to the $3 \mathrm{MT}(3-6 \mathrm{~min}$ test $\mathrm{p}=0.0052,>6$ min test $\mathrm{p}<0.0001)$. The test EPs regardless of test duration were not dependent on the type (sprinter, mid-distance, endurance) of cyclists ( $\mathrm{p}=0.1601$ ).

Table 3.7 CP/EP and W's for different CPTs (mean $\pm$ SD)

|  | Traditional | Constant-Power All-Out |  |  |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  |
|  |  |  | $<1$ min | $1-3 \mathrm{~min}$ | $3-6 \mathrm{~min}$ | $>6 \mathrm{~min}$ |
| CP or EP (w) | $289 \pm 54$ |  | $279 \pm 59$ | $274 \pm 52$ | $259 \pm 52$ | $249 \pm 48$ |
| Constant-Power W'e (J) |  |  | $8816 \pm 3426$ | $13135 \pm 5435$ | $18866 \pm 7611$ | $25773 \pm 13955$ |
| Unaccounted W'e (J) |  |  | $5859 \pm 3409$ | $2806 \pm 2006$ | $1550 \pm 1545$ | $1195 \pm 1387$ |
| Total W'e $(J)$ | $9440 \pm 4643$ | $15311 \pm 5397$ | $14674 \pm 3390$ | $15941 \pm 6476$ | $20417 \pm 8297$ | $26968 \pm 14624$ |



Figure 3.8 Comparisons of EP for difference duration CPT

Constant-power ${ }^{\prime}$ ' ${ }_{\mathrm{e}}$ for all of the tests appeared to increase with test duration, while significant differences were only observed between test durations over 3 min and Constant-power $\mathrm{W}^{\prime}{ }_{\mathrm{e}}(3-6 \min \mathrm{p}<0.0001,>6 \min \mathrm{p}<0.0001)$. On the contrary, the unaccounted $\mathrm{W}^{\prime}$ e showed a decreasing pattern as test duration was increased. Significant differences were observed between unaccounted ${ }^{\prime}$ ' ${ }_{\mathrm{e}}$ for test duration less than 1-min, as well as other test durations ( $1-3 \min \mathrm{p}=0.001,3-6 \min \mathrm{p}<0.0001,>6 \min \mathrm{p}<0.0001$ ).


Figure 3.9 Constant power $\mathbf{W}^{\prime}$ e for different CPT


Figure 3.10 Unaccounted $W^{\prime}$ e for different CPT

Total ${ }^{\prime}{ }^{\prime}{ }_{\mathrm{e}}$ (combining constant-power and unaccounted) value for all of the tests were higher from the traditional $\mathrm{W}^{\prime}{ }_{e}$, primarily due to the addition of the unaccounted $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$. However, only $>6$ min test $W^{\prime}{ }_{e}$ showed a significant difference from the 3 MT W ' $(\mathrm{p}=$ 0.0065).


Figure 3.11 Total $W^{\prime}$ for different CPT

### 3.3.3.2 Discussion

The results suggest that 3 MT and CPT do not provide an accurate measure of the traditional CP and W' ${ }^{\mathrm{e}}$. More specifically, mean power outputs during the final 30s are lower and $\mathrm{W}^{\prime}$ e are higher for all the Constant-Power all-out tests compared to the estimates of CP and $W^{\prime}$ e derived from the traditional power- $1 / \mathrm{t}$ model. However the same estimates determined from CPT with durations $\leq 3$ min are not different from those determined from the 3 MT .

Our observation of lower 3MT and CPT EPs (using the multiple comparisons with control procedure) is inconsistent with the observation reported by Dekerle [79]. Reanalyzing our data with Bonferroni post-hoc procedure, as performed in Dekerle's paper shows no statistically significant difference in 3MT EP $(p=0.0602)$ and CPT EP
for durations $\leq 3 \min (\leq 1 \min \mathrm{p}=0.1820$ and $1-3 \min \mathrm{p}=0.0641$ ) when compared to CP. This difference in analysis procedures led to incorrectly rejecting a hypothesis when the difference is in fact non-significant. Dekerle compared 3MT EPs and CPs for two different cadences ( 60 rpm vs. 100 rpm ) and applied the Bonferroni procedure to correct for type I error when significance was detected in the two-way ANOVA with repeated measures. In order to apply the Bonferroni procedure, the p-value will have to be adjusted by $\alpha / \mathrm{k}$, where k is the number of comparisons ( 6 in Dekerle's case) resulting in an adjusted p -value of $\mathrm{p}=0.0083$ (assuming $\alpha=0.05$ ). The inclusion of meaningless comparisons ( CP at 60 rpm vs. 3 MT at 100 rpm and CP at 100 rpm vs. 3 MT at 60 rpm ) can lower the p-value and lead to incorrectly rejecting a hypothesis, therefore, multiple comparisons with control procedure[132] was performed in our study.

CP has not been shown to be significantly different from the EP obtained from the constant-load 3MT [27]. However, in our isokinetic protocol, we observed a $4 \%$ lower power output when compared to CP. These two protocols differed in control of power outputs by the cadence in the constant-load mode, and by the force in the isokinetic mode. The end cadence that is exhibited in the constant-load 3MT as power output declines to a stable value is generally different from the subject's preferred cadence. It has been shown that an end cadence at or slightly below the subject's preferred cadence provides robust and accurate estimates of the CP model, but higher cadences reduce the CP [32]. Therefore, this difference in end cadence may explain the decrease in isokinetic 3MT EP, due to the power-velocity relationship of the muscles involved in cycling [133].

There is no difference in EPs between 3MT and CPT for durations $\leq 3 \mathrm{~min}$, and significantly lower power outputs were observed for 3-6 min and $>6 \mathrm{~min}$ durations (5.7\% and $8.9 \%$, respectively). Vanhatalo and colleagues observed that iEMG during the 3MT showed a progressive reduction throughout the test [63]. This maximum effort would require essentially all fibers to be activated synchronously from the onset of exercise, thus effectively eliminating the capability for progressive fiber recruitment [134, 135]. In contrast, the iEMG increased throughout the exercise bout during a 3 min work-matched CPT, indicating a progressive recruitment of higher-order (type II) muscle fibers with the
peak value measured at the limit of tolerance [63]. Thereafter, these fibers would become progressively fatigued, such that the power output at the end of the exercise bout would be predominantly generated by type I fibers $[16,135,136]$. Muscle fibers are categorized based on their contractile and fatigue properties [137-142]. The fatigue resistance rate differs for types of fiber, with fast-twitch fatigable (FF or type IIb) and fast-twitch fatigable intermediate (FInt or type IIx) fibers lasting $<1$ min and $<5 \mathrm{~min}$, respectively. Fast-twitch fatigue resistant (FR or type IIa) fibers express similar fatigue resistant characteristic to slow-twitch (S or type I) fibers with duration upward of 30min to hours for the slow-twitch fibers [143]. Therefore, at the end of the 3MT, we would expect only the FF fibers to be completely fatigued while some of the FInt and all of the FR and S fibers would still be activated. It would require almost five or greater than five minutes before the FF and FInt fibers are completely fatigued. Hence, at that time a true CP can be reached, which is predominantly produced by FR and $S$ fibers. The presented results support this interpretation with the observation of a lower power output for durations greater than six minutes. Thus, we suggest treating this lowered power output as a true CP , which delineates the border between exercise intensities requiring aerobic only and mixed aerobic and anaerobic energy production as defined by the Critical Power concept.

Concerning estimates of $\mathrm{W}^{\prime}$ e, data revealed an increasing trend for the constant power tests (Figure 3.9) which is inconsistent with the traditional interpretation of $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$ as a fixed anaerobic capacity [4]. For durations less than three minutes, the estimate for $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$ is no different from traditional $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$ however there is a $266 \%$ and $364 \%$ increase in $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$ for 3-6 $\min$ and $>6$ min test durations, respectively. This coincides with the duration at which EP significantly dropped to lower than the traditional CP, hence resulting in an increase in W' ${ }_{\mathrm{e}}$. The physiological implications are likely to represent depletion in substrates (e.g. muscle phosphocreatine) for shorter and higher power output test durations, and reuptake of metabolites (e.g. $\mathrm{H}^{+}$, inorganic phosphate, ADP, reactive oxygen species, and lactate) by neighboring oxidative muscle fibers at lower power output, longer duration tests [144, 145].

In addition, W' ${ }_{\mathrm{e}}$ may not be completely depleted at the termination (i.e. inability to maintain constant power output) of Constant-Power tests [19]. If subjects were to continue after the termination of the test due to failure to maintain the selected power output, power output would gradually decline to an asymptotic level. Typically, this additional energy expenditure is not accounted for which results in an underestimation of the complete W 'e. These unaccounted $\mathrm{W}^{\prime}{ }_{\mathrm{e}} \mathrm{S}$ were captured in our study, and a decreasing trend was observed as the test duration increased (Figure 3.10). More specifically, unaccounted ${ }^{W}{ }^{\prime}$ e associated with the 1-min test was larger than all the other unaccounted W'es. In such a short duration of time, the constant power W' ${ }_{\mathrm{e}}$ may represent the depletion of most, if not all, of the phosphagen (ATP-CP) system [146] and some of the anaerobic lactic system while the unaccounted W 'e may represent the remaining glycolytic ATP production (anaerobic lactic system). As the test duration increases ( $<3 \mathrm{~min}$ ), ATP-CP would occupy a smaller proportion of the constant power W' ${ }_{\mathrm{e}}$, and it would largely be represented by the anaerobic lactic system, and the remaining anaerobic lactic system (approximately 20\%) would be represented by the unaccounted $\mathrm{W}^{\prime}$.

The combination of the constant power and unaccounted ${ }^{\prime}$ 'e provided us with the complete $\mathrm{W}^{\prime}$ e, which was shown to be larger than the traditional W' ${ }^{\mathrm{e}}$. However, constant power exhaustive tests are prone to high variability [147], and taken together with the requisite multiple constant power exhaustive tests in the CP model, the compounded inherent variance would potentially lead to a less reliable calculation of ${ }^{\prime}$ ' ${ }_{e}$ for the traditional method compared to the ${ }^{\prime}$ ' ${ }^{\text {e }}$ assessed using 3MT [30]. Comparisons of CPTs and 3MT showed no difference in the anaerobic capacity except for durations longer than 6 minutes. As mentioned previously, reuptake of metabolites in the lower output, longer duration tests may contribute to the increase in capacity.

An alternative explanation derives from the observation that a reciprocal relationship exists between the development of the $\mathrm{VO}_{2}$ slow component, and the progressive reduction in the $\mathrm{W}^{\prime}[5,144,148]$. Given that the $\mathrm{VO}_{2}$ slow component is most pronounced in the lower region (higher intensity) of the severe domain [28, 46], the respective $\mathrm{W}^{\prime}$ e in the region would be lower in capacity. Similarly, if the output intensity
is lower (still in severe domain) then the $\mathrm{VO}_{2}$ slow component would be smaller, and the subject would reach exhaustion at a longer duration resulting in higher $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$. These results suggest that the traditional interpretation of $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$ as a fixed anaerobic work capacity may be outdated, as supported by work done by Vanhatalo in showing a decrease in $W^{\prime}$ e during exposure to hyperoxic gas [63] or an increase in W' ${ }_{\mathrm{e}}$ with priming performed exclusively in the heavy-intensity domain [149].

### 3.4 Overall Discussion

Two models; the relationship Critical Power model and the Constant-Power all-out Test, were proposed to investigate the performance-time relationship between sprint and endurance athletes, and to provide an alternate single day test protocol that could potentially estimate CP parameters accurately. Both models revealed an increasing trend for ${ }^{\prime}$ ' ${ }_{\mathrm{e}}$ with respect to time, which is inconsistent with the traditional interpretation of W'e as a fixed anaerobic capacity [4]. Estimates of W' ${ }^{\text {e }}$ derived from the CPT were larger than the traditional value but not different from the 3 MT for durations less than three min. Reuptake of metabolites $[31,144]$ and the presence of the $\mathrm{VO}_{2}$ slow component at lower exercise intensity [28, 46], in addition to the inaccuracy with quantifying anaerobic work in traditional CP model may have contributed to the increase in anaerobic capacity for the longer duration tests. The emergence of the $\mathrm{VO}_{2}$ slow component begins at exercise intensities above lactate threshold, while the proximity of power output to the Critical Power in the heavy intensity domain determines if the $\mathrm{VO}_{2}$ slow component will stabilize. Exercise intensity above Critical Power depends upon the interaction between the anaerobic capacity, $\mathrm{VO}_{2 \max }$, and the $\mathrm{VO}_{2}$ slow component to determine tolerable durations of exercise [150]. Increasing $\mathrm{VO}_{2 \max }$ and keeping the other parameters constant would effectively increase the scope for the $\mathrm{VO}_{2}$ slow component to develop, which should extend the time to exhaustion. Similarly, increasing the anaerobic capacity would increase time to exhaustion by increasing the amount of non-oxidative energy available throughout exercise (equivalent to an increase in W' ${ }^{\text {e }}$ ). Furthermore, decreasing the magnitude of the $\mathrm{VO}_{2}$ slow component would extend the time to reach $\mathrm{VO}_{2 \text { max }}$ which also extends time to exhaustion. Therefore, the $\mathrm{VO}_{2}$ slow component
being central to exercise tolerance could provide an explanation for the increasing nature of W' ${ }_{\mathrm{e}}$ with respect to time.

The CPT EP for durations less than three minutes was not different from the 3MT EP. However, it was slightly (4\%) lower than traditional CP, and a bigger drop of 9\% in EP was observed for CPT with durations longer than six min. This progressive decline in EPs could be attributed to the different fiber fatigue resistance rate from fast- to slowtwitch fibers [143]. At durations longer than six minutes, complete fatigue of fasttwitched and fast-twitch fatigable intermediate fibers would occur and the maximum power output would predominantly be produced by fast-twitch fatigue resistant and slowtwitched fibers. This phenomenon is shown in Figure 3.8 where a $\sim 5 \%$ drop in end power between the durations $1-3 \mathrm{~min}$ and $>6 \mathrm{~min}$ is observed. A similar trend was observed in, the relationship CP model study (Table 3.4), where the estimate of CP was much lower ( $\sim 25 \%$ ) than the traditional value. These estimates appeared to be in the same range as blood lactate threshold (LT) [31], defined as the point at which there was a $1-\mathrm{mmol} \cdot \mathrm{L}^{-1}$ increase in blood lactate concentration above resting value [151]. As exercise intensity increases above the LT, the utilization of glycogen for energy metabolism is elevated [152] and the accumulation of lactic acid also increases. Previous studies have also shown that utilization of fatty free acids (FFA) and triglycerides increase in exercise lasting more than $60 \mathrm{~min}[153,154]$, and endurance training increases the skeletal muscle's capacity to utilize FFA in order to delay the reduction in power output as a result of glycogen depletion [155]. Therefore, it appears power output decrements in the higher intensity domains may have been a disruption of the contraction process by metabolic acidosis as opposed to the influence of substrate depletion [156, 157]. Exercising at LT intensity can be maintained from 60-180 min [156, 158], whereas CP can only be sustained for around $30 \mathrm{~min}[18,42,48,51]$. Thus, CP has been established as the demarcation between heavy and severe exercise intensity domain [26, 27], while LT separates the regions that are associated to moderate and heavy exercise intensity [13, 129]. Therefore, the lower estimated CP in these studies corresponds closer to the theoretical definition as an intensity that can be maintained for a very long time without fatigue [3].

The relationship CP model study demonstrated a novel analysis method using a mixed model is a powerful tool that can be used to detect group differences more accurately. There is strong evidence that the relationship between intensity and duration is different from the traditional assumption of an inverse relationship ( $\mathrm{n}=1$ ) by the Critical Power model. This observation indicates a more gradual decline in power with respect to time than traditionally assumed, and the relationship constant appeared to be inversely associated with the caliber of athletes (i.e. training volume).

There was no difference observed in the performance-duration response between the sprint and endurance group in the three studies. Moreover, the relationship constant from the relationship CP model showed no significant difference, and the duration of 135 s for the all-out test was shown to be sufficient for both groups to estimate CP parameters. The group effect in the constant power test also showed no difference. However, performance differed fundamentally between sprint- and endurance-trained athletes as noted by Bundle [34], and this was also evident in both the relationship CP model and shorter duration all-out test studies that we performed. Our results demonstrating higher anaerobic capacity and lower aerobic output for the sprint group relative to the endurance group are consistent with observations from other previous studies, which similarly reveal that endurance-trained athletes can perform at high rates for longer duration or sprint-trained athletes demonstrate superior anaerobic performance on high intensity short duration exercises [35, 36].

## 4 Conclusion

In summary, the 3-min all-out test addressed the time-consuming multiday testing protocol of the traditional CP model. However, the mentally and physically exhaustive nature of the 3-min all-out test deters repeated testing, which is a concern since it reduces the ability to use the test as a regular fitness monitoring tool. Consequently, this assessment approach is not widely employed. Two scientifically grounded approaches, which include the Constant-Power all-out test with time duration less than three minutes and the 2.5 minute all-out test, were proposed that are more accessible to measure the aerobic (CP) and anaerobic ( $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$ ) fitness.

The relationship CP model study demonstrated a novel analysis method using a mixed model, which is a powerful statistical tool that can be utilized to detect group differences more accurately. The results showed a deviation in the performance-time relationship from the current assumption. Although the relationship was not different between the 2 groups (sprint and endurance), the aerobic and anaerobic components were; providing us with the impetus to commence the investigation of the type of athletes being tested, and not simply assuming similar responses. This relationship seemed to be associated with the muscle fiber shifting from fast- to slow-twitch as a result of high volume endurance training.

## 5 Future Directions

The Critical Power model and other extensions have been used to quantify one's aerobic and anaerobic energy system in order to predict performances and to monitor fitness status. However, testing is primarily done on a generic cycle ergometer in a laboratory setting and it may be inconvenient for athletes to travel to the testing facility. Furthermore, it is a nuisance for the athletes to be improperly fit to the laboratory based equipment, and this type of testing interrupts their structured training schedule. The CP parameter has been validated with a 3 MT on an indoor cycling trainer, however, the $\mathrm{W}^{\prime}{ }_{\mathrm{e}}$ parameter appeared to be different from the values estimated from the laboratory setting [31]. To my knowledge, there is no study in which CP parameters are adequately compared in both testing environments. A protocol that is transferrable to the field (i.e., moving bicycles) can promote the utilization of the CP model and ultimately aid athletes and coaches to more accurately quantify physiological variables.

As previously mentioned in the relationship CP model discussion, there seemed to be an association of the relationship constant, $n$, to the competitive level of the athlete. Training volume has been shown to increase as the level of the athlete increases, mostly through training frequency in sports like running and cross-country skiing, but also through increases in session duration in sports like cycling [122]. Logically, there should be a direct relationship between the relationship constant and training volume. The power-time relationship was compared between different levels of athletes, with swimmers at the elite level and cyclists and rowers at the university and club level; therefore, it would be difficult to make conclusive inference from such a comparison. More comprehensive studies would be required to investigate the relationship constant in different levels of athlete within one sport and possibly across the spectrum of many sports to claim generalization effects from training volume. CP determined from the relationship model should also be validated with other physiological correlates, which could then define the demarcation between the moderate and heavy intensity region.

It has recently been suggested that the precise value of W' is dependent on the available anaerobic capacity, $\mathrm{VO}_{2} \mathrm{max}$, and the $\mathrm{VO}_{2}$ slow component [150]. Each of these factors can be altered independently and/or in different proportions, which makes the prediction of the effect of an intervention on the W' ${ }^{\text {e complicated. In addition, several interventions }}$ aimed to alter one CP model parameter seem to affect the other [69, 78, 79]. The interrelationship between $W^{\prime}{ }_{e}$ and CP is therefore quite complex, and remains as a challenge to fully understand, and this relationship warrants further elucidation in the future.

The CP concept is relevant in any sporting event and has been suggested to be of most relevance to continuous activities lasting approximately 2 min to 30 min due the shortcomings of the model in its inability to describe the relationship well at the extremes of the power output range [121]. Furthermore, the CP model has been modified for intermittent exercise $[67,100,101]$ and therefore has potential applications for interval training and certain team sports, such as soccer, and rugby. In addition to the repeated sprint nature, some of the sports require athletes to play several games a day for multiple days. Therefore interventions to ensure athletes are at optimal physical state for the next game are crucial. Recovery time is inversely proportional to the degree of muscle fatigue [159], such that monitoring in-game athlete energy expenditure can prevent excessive fatigue and allow enough time to recover for the next game. One means to monitor this fatigue is with W' ${ }_{\mathrm{e}}$ of the CP model. Recently, a new model was developed monitor W' over time in response to intermittent exercise [67] and was successfully applied to fieldbased cycling session [109]. The model calculates the balance of W' ${ }_{\mathrm{e}}$ remaining at any given time by continuously quantifying the energy expended above CP and the recharging of $W^{\prime}{ }_{e}$ during recovery periods comprising exercise at intensities less than CP [67]. Similar approach can enable the real-time monitoring of energy levels during games.

As a direct result of the shorter duration all-out test study, the test has been successfully evaluated in our study of cyclists and more than 35 study participants have repeated our test protocol over five times in a four week period in a separate study demonstrating the
shorter test protocol is one that people are willing and able to repeat. Therefore the test has the capacity to serve as a successful fitness monitoring tool. In our unpublished data, CP was estimated accurately but not W' ${ }^{\prime}$ when the test is performed after an interval session. This versatility aspect of the test will enable more frequent monitoring without any interruption to the training plan.

## 6 References

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