Investigating the bioenergetic and mathematical determinants of the Critical Power model in elite cyclists.

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Boris James Raymond Clark

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Abstract

Background: The Critical Power model is used to monitor and predict the performance of elite cyclists. Using maximal power data from various durations the model calculates a maximal steady state intensity called Critical Power and a work capacity beyond this known as the W' (W-Prime). Much research has focussed on the bioenergetics of the Critical Power, however, less is known about the bioenergetic composition of the W'.

Aim: The key aim of this study was to investigate the bioenergetics of the Critical Power model**.** Secondary aims were to compare four different Critical Power models against each other and determine the relationship between $\dot{V}La_{max}$ and power output during extreme intensity exercise.

Hypothesis: It was hypothesised that measures related to anaerobic pathways (Peak power, $\dot{V}La_{max}$) would better predict W', while measures related to aerobic pathways (W_{max}, $\dot{V}O_{2max}$, VT^1 and VT^2 power outputs) would better predict CP.

Methodology: Ten elite national level male cyclists participated in the study, with nine completing the study. Participants reported to the laboratory on three occasions separated by at least 24h, over a period of less than three weeks. In the first session participants completed a test to determine $\dot{V}La_{max}$, a 1-min time trial (TT), and a ramp test to determine $\dot{V}O_{2max}$, W_{max}, VT_1, and VT_2. In the subsequent two sessions participants completed maximal four and ten-minute TT's which were used to determine Critical Power and W' using the Linear Time-Work model for the primary analysis. In the secondary analysis four Critical power models were formulated from all three TT efforts and compared against each other, while the 1-min TT was used to assess extreme intensity exercise capability.

Results: CP was strongly correlated with the aerobic variables VT_1 (r=0.72, r^2=0.52, p=0.028), VT_2 (r=0.85, r^2=0.73, p=0.0035), $\dot{V}O_{2max}$ (r=0.91, r^2=0.83, p=0.0007) and W_{max} (r=0.92, r^2=0.84, p=0.0005). Power outputs at CP and VT_2 were not significantly different for absolute (327 ± 41 vs 330 ± 37W, p=0.91) or relative (4.66 ± 0.54 vs 4.72 ± 0.58$W \cdot kg^{-1}$, p=0.95) power output. The only significant relationships with W' were with $\dot{V}O_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)($r$=-0.67, r^2=0.45, p=0.047) and CP ($W \cdot kg^{-1}$) (r=-0.69, r^2=0.47, p=0.042).

Using variables related to bioenergetics multiple regression significantly predicted CP(W·kg^{-1}) (p=0.001) and W' (p=0.034). The relative power output (W·kg^{-1}) in the 1-min TT was significantly related to $\dot{V}La_{max}$ (r=0.85, r^2=0.73, p=0.0016), although work completed above CP in this effort was significantly less than W' (p=0.0008). All four Critical Power models were found to produce significantly different (p<.001) Critical Power and W' values, however, Critical Power was not significantly different to VT_2 for any model (p=0.10-0.93). $\dot{V}La_{max}$ could be significantly predicted from regression equations using both absolute (p=0.011) and relative (p=0.004) lactic interval power.

Conclusion: The Critical Power is further reinforced as an aerobic parameter, while W' categorisation is more difficult due to the involvement of maximal aerobic capability and both anaerobic systems. W' was negatively correlated with measures of relative aerobic capability ($\dot{V}O_{2max}$ ml·min^{-1}·kg^{-1}, CP W·kg^{-1}) and has been related positively to lean mass in previous research, indicating a possible link between muscle mass and W'. The relationship between $\dot{V}La_{max}$ and relative 1-min TT power output (W·kg^{-1}) supported the extreme intensity exercise domain being highly related to glycolytic capacity. The fact W' could not be depleted in this effort was hypothesised to occur due to a delay in the $\dot{V}O_2$ kinetics and therefore a delayed contribution of the Critical Power to the effort. All models produced significantly different outputs for Critical Power and W'. Although the Critical power was not significantly different to VT_2 for any model, the individual variation in Critical Power between models and lack of criterion measure with which to validate an accurate W' makes it difficult to recommend a best model. Finally, the $\dot{V}La_{max}$ was significantly predicted by power over the lactic power interval of the $\dot{V}La_{max}$ test which may be useful for those wishing to measure the $\dot{V}La_{max}$ of elite cyclists without specialist equipment.

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List of Abbreviations

ATP = Adenosine Triphosphate

AMP = Adenosine Monophosphate

CP = Critical Power

CV = Coefficient of variation

PCR = Phosphocreatine

$P_{ET}CO_2$ = End-tidal Partial Pressure of Carbon Dioxide)

$P_{ET}O_2$ = End-tidal Partial Pressure of Oxygen)

P_{max} = Maximum instantaneous power output

Rpm = Revolutions per minute

s = Seconds

TT = Time trial

$\dot{V}E \cdot \dot{V}CO_2^{-1}$ = Ventilatory Equivalents for Carbon Dioxide).

$\dot{V}E \cdot \dot{V}O_2^{-1}$ = Ventilatory Equivalents for Oxygen)

$\dot{V}La_{max}$ = Maximum lactate production rate

$\dot{V}O_2$ = Oxygen consumption

$\dot{V}O_{2max}$ = Maximal Oxygen Consumption

VT_1 = First ventilatory threshold

VT_2 = Second ventilatory threshold

W = Watt

W' = Watt prime

WAnT = Wingate Anaerobic Test

Chapter 1: Introduction

The key moments in many endurance sports demand work at intensities well beyond where a steady state can be maintained (Joyner & Coyle, 2008; Mujika, 2017). Road and track cycling are both examples of endurance sports with intermittent power profiles, where the key moments rely on the ability to perform and maintain high intensity power outputs (Jeukendrup, Craig, & Hawley, 2000). To classify these different work intensities the concept of exercise intensity domains has been developed. There are four primary exercise domains; the moderate intensity domain (below first ventilatory threshold); the heavy intensity domain (between the 1st and 2nd ventilatory thresholds) ; the severe intensity domain (above the 2nd ventilatory threshold); and the extreme intensity domain (intensity where the effort is either completed or fatigue develops before $\dot{V}O_{2max}$ is reached) (Hill, Poole, & Smith, 2002; Jones & Vanhatalo, 2017). Exercise in the severe and extreme intensity domains is associated with the high-power bursts which are decisive during the key moments during competition, however, there is large individual variation in the duration cyclists can exercise in these intensity domains before exhaustion occurs (De Lucas, De Souza, Costa, Grossl, & Guglielmo, 2013; Vanhatalo, Jones, & Burnley, 2011).

These intensity domains are traditionally bound to laboratory testing which includes physiological indicators of effort in relation to work rate. More recently this includes the components of the Critical Power concept (Critical Power and W').

Critical Power (CP) is considered the maximal intensity at which a metabolic steady state can be achieved for a prolonged period (30-60-min) and demarcates the transition between heavy and severe intensity domains (Dekerle, Baron, Dupont, Vanvelcenaher, & Pelayo, 2003; Moritani, Nagata, Devries, & Muro, 1981). The CP is considered an aerobic parameter of performance and is highly correlated with $\dot{V}O_{2max}$ (Heubert et al., 2005; Jones, Vanhatalo, Burnley, Morton, & Poole, 2010; Moritani et al., 1981). Work rates beyond this steady state result in a continued increase in oxygen consumption ($\dot{V}O_2$), blood lactate concentrations, and metabolite accumulation associated with subsequent exhaustion (Black et al., 2017; Poole, Ward, Gardner, & Whipp, 1988). The amount of work able to be performed beyond CP in this unstable environment is the W'. The W' can be utilised by expending a small amount of energy over CP for a longer duration, or depleted rapidly by expending a large amount of energy over CP for a shorter duration, but the total work completed above CP will always be the same (Monod & Scherrer, 1965; Moritani et al., 1981).

This introduces the question;

What are the physiological/metabolic determinants of the W'?

There is little research investigating the physiological components of the W'. What research there is looks to confirm the anaerobic nature of the W' or has estimated anaerobic capacity through mechanical measures of performance. Nebelsick-Gullett, Housh, Johnson, and Bauge (1988), compared the W' against the Wingate Anaerobic test (WAnT). Participants (n=25) completed a 30-s WAnT test, which is an 'all-out' 30-s cycle ergometer sprint test (Inbar, 1996). This was compared to the W' derived from three rides to exhaustion at different intensities. Strong correlations were found between mean WAnT test power and the W' (r=0.74, p<0.05). The maximal accumulated oxygen deficit is another technique used to quantify anaerobic capacity. One of the few studies to investigate the relationship between W' and maximal accumulated oxygen deficit was carried out by Hill and Smith (1993), who found anaerobic capacity measures of maximal accumulated oxygen deficit and W' were not significantly different, supporting the association between W' and anaerobic capacity.

The magnitude of the W' has also been compared under normal (FiO_2=0.21) and reduced O_2 concentrations (FiO_2=0.09-0.15) (Dekerle, Mucci, & Carter, 2012; Moritani et al., 1981; Simpson, Jones, Skiba, Vanhatalo, & Wilkerson, 2015). In theory if the W' is fully anaerobic it would be unaffected by the hypoxic condition. Participants in these studies performed tests to determine CP and W' under both conditions, with the mean results indicating no significant change in W'. However, large individual variability was displayed. Individual W' changes ranged from -44% to +66%, meanwhile the CP was significantly decreased under hypoxia by 6-55.6% across these studies, further illustrating the aerobic nature of the CP.

The WAnT conflates mechanical power output with anaerobic capacity, while the hypoxic tests strengthen the theory of W' as an anaerobic parameter, however, there is no precise quantification of the W' as an anaerobic capacity with either of these measures. It has also been suggested that the WAnT test is too short to fully deplete the anaerobic glycolytic capacity and also contains a significant aerobic contribution (Beneke, Pollmann, Bleif, Leithäuser, & Hütler, 2002; Katch, Weltman, Martin, & Gray, 1977). Using maximal accumulated oxygen deficit appears to allow an accurate quantification of W' as an anaerobic capacity, however, more research is needed to confirm the validity and accuracy of this relationship and this does not provide insight into the composition of the W' from an individual energy system perspective.

It has been proposed by that the glycolytic capacity can be measured through the use of a $\dot{V}La_{max}$ (maximal lactate production rate) test (Adam et al., 2015; Hauser, Adam, & Schulz, 2014; Nitzsche, Baumgärtel, & Schulz, 2018). This allows a quantification of the strength of the glycolytic system alone rather than calculating an overall anaerobic capacity which includes both the adenosine triphosphate-phosphocreatine (ATP-PCr) and anaerobic glycolytic systems. Therefore, to better understand the bioenergetics of the CP and W', this research aims to measure key physiological indices of performance and their relationship with the CP model components. It also aims to determine how $\dot{V}La_{max}$ relates to extreme intensity exercise, and how different CP models influence the CP and W' values.

Chapter 2: Literature Review

2.1. Energy Systems Overview

To understand the energetics during exercise in the severe and extreme intensity domains where the W' occurs it is necessary to first consider the energy production pathways in the body. There are three distinct, yet closely linked energy production pathways. These are the ATP-PCr, anaerobic glycolytic, and aerobic systems (Gastin, 2001).

During exercise, the breakdown of adenosine triphosphate (ATP) is required for muscle contraction, meaning to continue exercise ATP needs to be continually regenerated. With the demand for ATP considerably greater during exercise than at rest, it is necessary to have a continuum of energy systems (Figure 1) enabling rapid and prolonged ATP supply (Baker, McCormick, & Robergs, 2010).

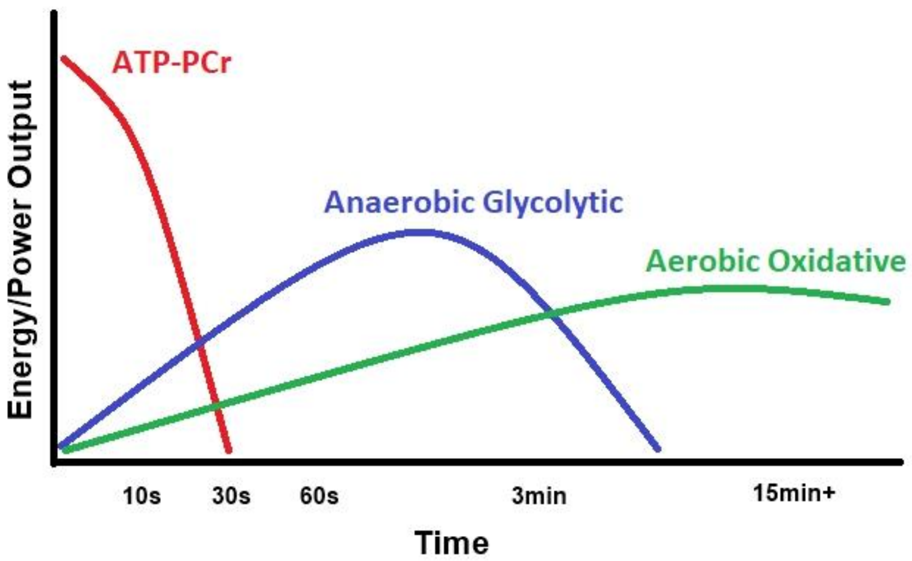

Figure 1. Visual representations of utilisation of the three energy systems over various exercise durations.

The fastest ATP producing, but lowest capacity system is the ATP-PCr system. This is an anaerobic system which uses ATP stored in the muscle cell and the splitting of phosphocreatine (PCr) to rapidly provide ATP at high rates, reaching maximal production rates in less than a second (Gastin, 2001). The capacity of this system is extremely limited with the majority of the system's capacity able to be exhausted in less than 15-s (Gastin, 2001; Wells, Selvadurai, & Tein, 2009). The phosphocreatine system is the primary system used over the first seconds of intense exercise (Jeukendrup et al., 2000; Wells et al., 2009). It's reduction stimulates oxidative phosphorylation (Bailey, Vanhatalo, Dimenna, Wilkerson, & Jones, 2011), as well as producing Adenosine Monophosphate (AMP) (Baker et al., 2010).

The bodies other anaerobic system is the glycolytic system. The production of AMP by the ATP-PCr system activates the enzymes phosphorylase and phosphofructokinase. This allows glucose to be broken down for a net gain of two ATP (Baker et al., 2010). This system is a large contributor to the energy demand during intense exercise up to several minutes, covering around 35% of the energy required for a maximal 10s effort, 65% for a 30s effort, and approximately half the ATP required for a maximal 1-2-minute effort (Jeukendrup et al., 2000; Wells et al., 2009). The glycolytic system contributes to energy production over longer time durations as well, contributing around 10% of the energy production over a maximal 10-minute effort, and continuing to be activated at low levels over all durations (Wells et al., 2009). The reactions yielding ATP from the breakdown of one glucose molecule results in the production of two pyruvate molecules or two lactate molecules depending on oxygen availability (Baker et al., 2010; Wells et al., 2009).

The slowest ATP producing, but highest capacity system is the aerobic system. The aerobic system can generate ATP from two main sources; lipids, or oxidation of pyruvate which has been reduced from glucose or glycogen. This ultimately results in 'mitochondrial respiration' where oxygen is mixed with either of these fuel sources in the mitochondria to produce ATP (Wells et al., 2009). Use of the aerobic system ultimately produces acetyl-CoA which enters the Krebs cycle to produce ATP (Purdom, Kravitz, Dokladny, & Mermier, 2018). In the presence of oxygen the pyruvate produced through glycolysis is converted into acetyl-CoA which will enter the Krebs cycle to generate ATP (Wells et al., 2009). In the absence of oxygen, the pyruvate accepts one hydrogen ion to become lactate. Lactate acts as a pH buffer before being catalysed by lactate dehydrogenase back into pyruvate when oxygen becomes available. It will then be converted into acetyl-CoA, and enter the Krebs cycle (Jacobs, Meinild, Nordsborg, & Lundby, 2013). Lactate may also be formed even when there is an excess of oxygen available and consumed directly by the mitochondria (Brooks, 2020).

All three energy production pathways act distinctly to generate ATP, yet all rely on each other for continued activation. When considering maximal steady state efforts, the aerobic system covers a greater proportion of the energy demand as the effort duration becomes longer, while the glycolytic and ATP-PCr systems cover a greater proportion of the energy demand of shorter efforts. Thus, in the CP model it seems likely the CP is related more to aerobic capacity, whilst the W’ may be related to the capacity and activation of the two anaerobic systems as well as continued clearance of metabolites by the aerobic system.

2.2 Energy system utilisation during exercise

The utilisation of different energy systems in sport depends on factors such as intensity, duration, tactics, terrain, and the individual/training characteristics of the athlete. As the intensity increases both the aerobic and glycolytic contribution to energy production will increase. The glycolytic contribution will increase exponentially and respond quickly as the intensity rises, but will decrease as the athlete fatigues or as the phase II kinetics and/or slow component of the aerobic system reach the desired work rate (Burnley & Jones, 2007; Wilkerson, Koppo, Barstow, & Jones, 2004).

During exercise in the moderate intensity domain the $\dot{V}O_2$ will stabilise at a level equivalent to the imposed work-rate. In the heavy exercise domain $\dot{V}O_2$ will display a slow component, where $\dot{V}O_2$ rises over a period of 10-20 minutes before stabilising at a steady-state, while in the severe intensity domain the slow component will continue to climb until $\dot{V}O_{2max}$ is reached (Figure 2) (Burnley & Jones, 2007). The aerobic contribution to the energy demand continues to increase until $\dot{V}O_{2max}$, however, the rate of glycolysis at these intensities outstrips that of the aerobic systems ability to combust the resulting lactate production, leading to an accumulation of hydrogen ions (H^+) (Black et al., 2017; Mader & Heck, 1986).

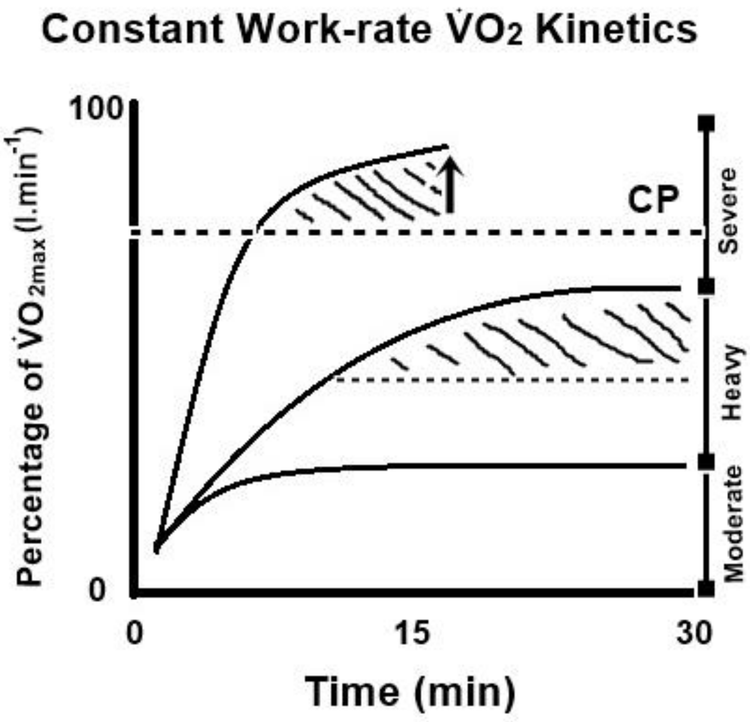

Figure 2. Demarcation of the exercise intensity domains and visualisation of the $\dot{V}O_2$ slow component and kinetics during constant work-rate exercise (Jones et al., 2011).

Only some sports involve a performance resulting in a steady work-rate throughout. Many sports are intermittent in nature, requiring a mix of high intensity bursts, steady state efforts, and low intensity periods. In sports that have an intermittent intensity distribution the activation of the different energy systems is more complex as is the response in the muscle cell. During intermittent exercise ATP and PCr concentrations in the muscle decrease as intense bursts of work are performed. When recovery periods are interspersed in the exercise these concentrations begin to recover towards their previous levels, thus making this energy pathway available again for multiple intense bursts (Chidnok, DiMenna, et al., 2013). Similarly, a return towards homeostasis of muscle pH, lactate production through glycolysis, and net lactate combustion from the aerobic system occurs when the intensity decreases below the maximal metabolic steady state intensity (Grossl, de Lucas, de Souza, & Guglielmo, 2012; Mader & Heck, 1986). While recovery towards homeostasis occurs when the intensity decreases, the ability to repeat high intensity workloads such as sprints decreases after multiple exertions in the severe and extreme intensity domains. This means pacing strategies and tactics to persevere these abilities is an important part of competition.

2.3 Physiological and Mechanical Demands of Road and Track Cycling

Endurance road and track cycling exhibit intermittent power profiles and large variability in the extent to which each energy system is utilised at any one time. An event such as 4km individual pursuit on the track lasts fractionally over four minutes for an elite rider and is paced to achieve the fastest possible time. The ATP required for the event is primarily generated aerobically, comprising 85% of the total ATP, while the anaerobic systems play an important but comparatively smaller role, with approximately 14% being generated through glycolysis, and 1% from the ATP-PCr system (Craig & Norton, 2001; Jeukendrup et al., 2000). Riders reach power outputs of around 1000 W for 10-15-s from a standing start, with the remainder of the ride varying between 450 and 600 W every 4-5-s as power output fluctuates between the corners and straights of the track. Mean power output is normally around 500 W (Craig & Norton, 2001). While power output in the individual pursuit can vary significantly between straights and corners of the track, the power output for the entire event is ridden in the severe intensity domain. In contrast, the team pursuit lasts just under four minutes for an elite rider, also involving a 1000 W or greater 10-15-s effort from a standing start, followed by 2-3 turns on the front of the team around 600 W for approximately 30-s, and about 1-1.5 minutes in the draft between 350-400 W (Craig & Norton, 2001). 350-400 W is around the top of the heavy intensity domain for most elite riders (Sallet, Mathieu, Fenech, & Baverei, 2006). This results in the event transitioning multiple times between heavy and severe intensity domains. The team in comparison to the individual pursuit has a much higher anaerobic ATP contribution, with an estimated glycolytic contribution of 24%, aerobic of 75%, and ATP-PCr the same at 1% (Jeukendrup et al., 2000). Despite the two events being the same distance and similar duration, they display very different power, metabolic, and force velocity requirements due to the different speed and gear selection of the event. The duration of the event is therefore just one factor in determining the physiological requirements of an event.

Many riders who compete on the track also compete in road cycling competitions. Road cycling also has an intermittent power profile and energy system utilisation, however, races tend to last hours at a time and can include multiple stages over multiple days in tour racing. Races vary in terrain with flat races, hilly races, criteriums, and time trials, each with different power requirements, energy demands (Lucía, Hoyos, & Chicharro, 2001). Different riders specialise in different events and course types owing to the different physiological and tactical requirements for each event type.

Criteriums have the highest mean power of the bunch races, owing to their generally short duration and thus aggressive nature (Ebert, Martin, Stephens, & Withers, 2006). Often the courses are short with many corners meaning the power profile is very intermittent and the ability sprint and recover repeatedly is important. Compared to criteriums road races involve proportionately less time spent in the severe intensity domain and more time spent in the heavy intensity domain. The total time spent in the severe intensity domain is still substantial, often totalling around one hour in professional races. Races can also include explosive sprints to form a break-away or to sprint at the finish of a race (Tanaka, Bassett Jr, Swensen, & Sampedro, 1993; Van Erp & Sanders, 2020). In both one-day races and stages of 'grand-tours' which consist of 21 stages over three weeks of racing, the largest amount of time is spent at power outputs associated with the moderate intensity domain. Important parts of the race are still comprised of time spent in the severe and extreme intensity domains which comprise around 5-15% (10-30-min) of the total race duration (Rodríguez-Marroyo, García-López, Juneau, & Villa, 2009; Van Erp & Sanders, 2020). It is therefore important cyclists have the capacity to ride for long periods in the moderate and heavy intensity domains while maintaining the capacity to perform large amounts of work in the severe and extreme exercise domains.

2.4 Critical Power Model

Physiological testing provides a wealth of data enabling categorisation of performance ability/development, exercise intensity prescription and quantification of prescribed training outcomes. Testing the anaerobic capacity and power of cyclists can take many forms such as the WAnT, maximal accumulated oxygen deficit, and $\dot{V}La_{max}$, while common tests to assess the aerobic condition and 'thresholds' of cyclists include testing the $\dot{V}O_{2max}$, onset of blood lactate accumulation, maximal lactate steady state or ventilatory threshold one and two (VT_1 and VT_2, respectively).

Many of these tests require specialist equipment, retained in laboratories, operated by specialist staff, resulting in substantial costs and time demands. The advent of widely available, low-cost, power meters for everyday use has seen trainers, scientists and athletes attempt to understand metabolic capacities through power-meter data logged during real-world training and racing rather than relying on laboratory testing. This data is now processed through an automated system of web-based applications.

One such method of gaining insight into the capacities of a cyclist is the critical power model developed from the work of Monod and Scherrer (1965). They proposed a synergistic muscle group has a threshold intensity which could be sustained without fatigue, since termed the CP, and a fixed work capacity above CP, since termed the W'. This resulted in a linear relationship between work and effort duration. Moritani et al. (1981), extended the CP concept to cycle ergometry. Participants (n=16) performed a series of tests riding at set power outputs to exhaustion. The work completed and duration of each ride before fatigue resulted in a linear relationship with r^2 values ranging from 0.982 to 0.998, indicating the CP concept of a synergistic muscle group could also be applied to cycling. The authors also found no significant difference between VT_2 and CP power outputs ($r=0.907$, $P<0.01$), which was subsequently supported by Dekerle et al. (2003), supporting the notion that CP is aligned with a 'threshold' intensity.

There are four models commonly used to calculate CP and W' when multiple trials are performed, with each model providing slightly different estimates of these parameters. These models are the linear-timework (linear-TW) model, linear-power model (linear-P), hyperbolic-2 parameter model (Hyp-2P), and hyperbolic-3 parameter model (Hyp-3P). The linear models form a linear regression line, and the non-linear/hyperbolic models form a hyperbolic curve. The CP and W' derived from the different models can vary between models depending on the participants data (Bergstrom et al., 2014; Bull, Housh, Johnson, & Perry, 2000; Gaesser, Carnevale, Garfinkel, Walter, & Womack, 1995). This is supported in figure 3 A-D where data of a single participant from the current studies data is presented. The formulas relevant to each modle are presented in Table 1.

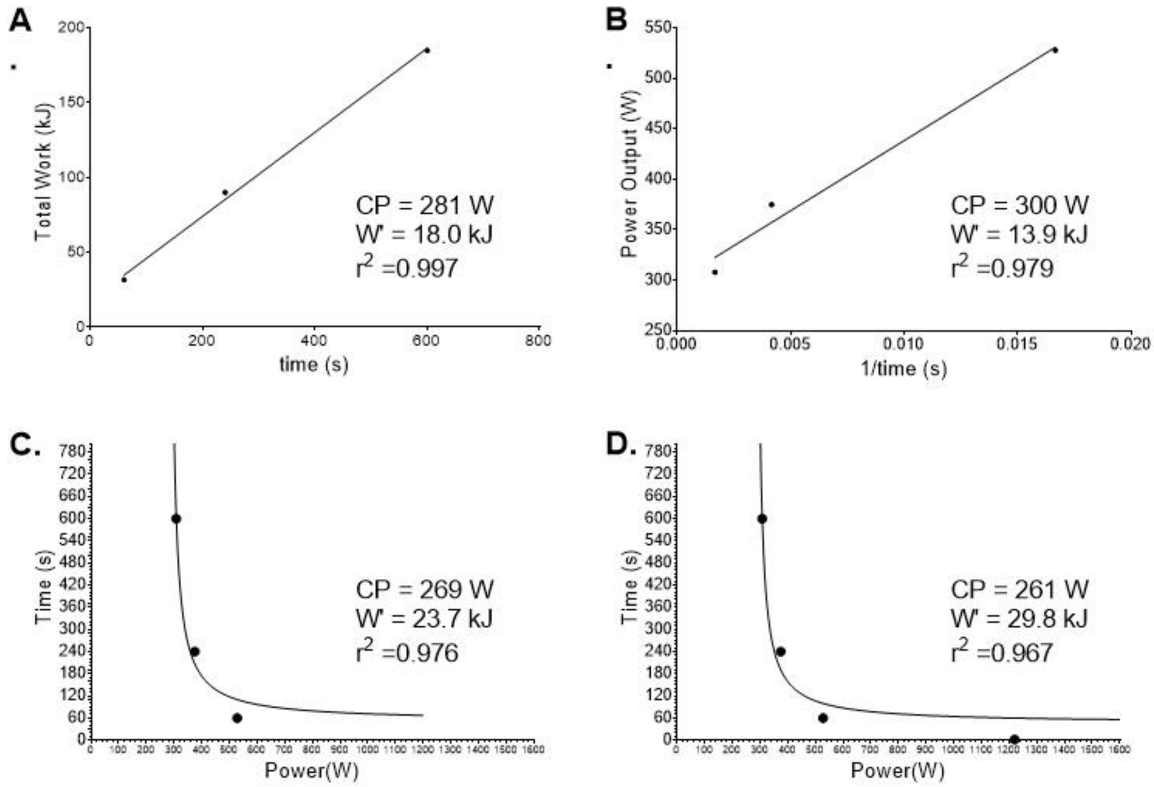

Figure 3. Graphical representation of the 4 different CP models using a single participants data from the current study showing how CP and W' estimates vary between models. **A:** Linear-TW model. **B:** Linear-P model. **C:** Hyp-2P model. **D:** Hyp-3P model.

Table 1. Formulas to calculate CP and W' for various CP models

Linear-TW	W_{lim} = W'+(CP*t)
Linear-P	PO = W'*(1/t) + CP
Hyp-2P	t = W'/(PO-CP)
Hyp-3P	t = (W'/PO-CP) + (W'/CP-P_{max})

W_{lim} = Maximum amount of work able to be completed in an effort; W' = Watt-Prime; CP = Critical Power; t = Time(s); PO = Power output; P_{max} = Maximum instantaneous power output

The original application of the CP concept to cycle ergometry by Moritani et al. (1981), used the linear-TW work model. The linear-TW model plots work against time, while the hyperbolic models plot power against time or 1/time in the case of the linear-P model. This allows an easy visualisation of the possible work-rate and duration it can be sustained for when analysed graphically, although this information can easily be derived by rearranging the relevant equation in table 1 for each model. The Hyp-3P model adds the parameter P_{max}, which is the maximum instantaneous power output. This helps overcome the assumption that all of the W’ can be utilised over extremely short time periods, as well as developing a relationship between the maximum power available at any given time and the W’ remaining (Hugh Morton, 1996). This relationship also implies that at exhaustion it is possible not all the W’ has been depleted, for example if the maximum power available drops below the required work-rate in a time to exhaustion test the participant will fatigue even though some W’ is still remaining.

Bergstrom et al. (2014), found the linear models tend to produce higher estimates of CP and lower estimates of W’ than the hyperbolic models (CP; Linear-P = 184 ± 43W, Linear-TW 181 ± 42W, Hyp-2P = 176 ± 40W, Hyp-3P = 174 ± 41W; W’; Linear-P = 11.4 ± 6.1kJ, Linear-TW = 12.2 ± 5.8kJ, Hyp-2P = 14.6 ± 5.5kJ, Hyp-3P = 15.2 ± 5.6kJ; CV-CP = 2.55%, CV-W’ = 13.7%). Similar results (Coefficient of variation (CV) -CP = 5.95%) were obtained by Bull et al. (2000) and Gaesser et al. (1995) (CV-CP = 8.1%, CV-W’ = 57.5%), who noted that the W’ of the Hyp-3P model was often 2-3 times larger than that produced by the linear models. The Hyp-3P model produces the lowest CP estimates among the models (Bergstrom et al., 2014; Bull et al., 2000). It may also produce the CP value closest to VT_2, providing the time durations of each effort are chosen appropriately (Gaesser et al., 1995). The Hyp-3P model is however the most complex to calculate and requires an extra test to determine P_{max}. The outcomes of the CP and W’ estimates therefore depend on both the model used to calculate them, and what testing procedures and durations are used.

2.5 Critical Power Testing

The ‘traditional’ protocol to determine CP and W’ in cycle ergometry involved the use of ‘square-wave’ bouts of exercise, where the participant cycled at a set power output until exhaustion (Moritani et al., 1981). Studies which used this methodology typically included 4-5 square-wave bouts (Moritani et al., 1981; Morton, 2006). As participants rode to exhaustion in each square-wave exercise bout these tests were very physically demanding. This posed the question;

How many exercise bouts are required to accurately determine the CP and W’?

Housh, Housh, and Bauge (1990), found it was possible to accurately determine CP and W’ from just 2 efforts, provided the test durations were varied in length by at least 5-

min and between one and ten minutes in duration. This is supported by the work of Simpson and Kordi (2017), who found adding a third effort of five minutes to the already completed three and 12-min efforts did not meaningfully change the estimated time-work relationship. A single un-paced ‘all-out’ exercise bout of three minutes in duration has also been proposed to estimate the CP and W’ (Bergstrom et al., 2012; Burnley, Doust, & Vanhatalo, 2006). The theory behind the three minute ‘all-out’ test is that the W’ is fully utilised before the conclusion of the test. This means the only contribution to power at the end of the test is from the CP, with the work done above the CP in the test being from the W’. This test appears valid for untrained or lightly trained participants but appears to significantly overestimate CP and underestimate W’ in well trained cyclists (Bartram, Thewlis, Martin, & Norton, 2017; McClave, LeBlanc, & Hawkins, 2011).

The recovery time between exercise bouts is another important factor when considering testing protocols. The influence of recovery duration on the CP and W’ was tested by Bishop and Jenkins (1995). Participants (n=9) performed three trials to exhaustion at power outputs expected to result in fatigue between 1-10-min. It was found CP did not differ between 3-h and 24-h recovery periods (170.6 ± 39.8 vs 171.6 ± 40.7 W) as a mean value and between participants, whereas W’ displayed similar mean values (10.8 ± 2.5 vs 12.0 ± 3.0 kJ), but large variation between participants with no clear trend in how the W’ was affected. Analysis of variance (ANOVA) revealed trial order has no effect on W’ estimates. Karsten, Hopker, et al. (2017), tested 30-min, 3-h, and 24-h recovery periods. Neither CP or W’ were significantly different between recovery durations (CP; 277 ± 26 vs. 274 ± 25 W. W’; 15.2 ± 4.7 vs. 15.0 ± 4.2 kJ), but W’ was deemed unacceptably different between 3-h and 24-h recoveries when individual participants data was considered. Larger variation in W’ was found when only 30-min recovery was provided (15.2 ± 4.7 vs. 11.3 ± 3.5 kJ) although this was also not statistically significant. There was again no significant or noteworthy difference in CP when only 30-min recovery was provided. It was concluded 24-h was needed to ensure accurate W’ values were obtained.

2.6 Metabolic Composition of the CP and W'

Despite a plethora of research and common place use of the CP model in performance modelling there are still many unknowns about the physiology underpinning it, particularly the metabolic composition of the W'.

The CP is closely linked to the aerobic capacity (Jones et al., 2010; Moritani et al., 1981), is strongly correlated with 'threshold' markers such as maximal lactate steady state (Jones et al., 2010; Pringle & Jones, 2002), and is a similar intensity to VT_2 (Dekerle et al., 2003; Gaesser et al., 1995). Exercise at CP results in a steady state $\dot{V}O_2$ after an initial slow component (Keir et al., 2015; Poole et al., 1988). These characteristics align with the physiology underpinning these physiological 'threshold' measures, suggesting the metabolic composition of the CP is highly aerobic and can act as the demarcation point between the heavy and severe intensity domains (Jones & Vanhatalo, 2017; Vanhatalo et al., 2011). The precision with which CP estimates these intensities, however, depends on the method used to calculate the CP (Gaesser et al., 1995).

The W' is closely related to anaerobic capacity (Hill & Smith, 1993; Nebelsick-Gullett et al., 1988; Vandewalle, Vautier, Kachouri, Lechevalier, & Monod, 1997). This is supported by training studies which aimed to determine the influence of resistance training, expected to increase the anaerobic capacity and power, on the work-time relationship. Bishop and Jenkins (1996), had participants (n=16) complete either no additional exercise (n=8) or 6 weeks of resistance training (n=8). After training W' increased significantly (21.5 ± 3.3 to 29.0 ± 3.3 kJ) while no change was seen in the control group (19.7 ± 2.3 to 18.4 ± 1.9 kJ) or for CP of either group. Similar results were presented by Sawyer et al. (2014), who also had participants (n=21) perform either no additional exercise (n=7) or an eight week resistance training programme. The W' of the resistance training group increased significantly (16.7 ± 4.9 to 24.4 ± 8.5 kJ) while no change occurred for the control group (14.5 ± 5.8 to 15.2 ± 7.0 kJ) or for CP in either group. Further linking the W' to anaerobic capacity is its improvement after cycling intervals designed to stress the anaerobic systems. Jenkins and Quigley (1993), had participants (n=15) perform either no additional training (n=7) or interval training (n=8) consisting of 5x60s maximal efforts separated by five minutes passive recovery, 3x/wk. for eight weeks. This increased W' significantly for the training group (13.4 ± 3.2 to 20.0 ± 3.8

kJ), while no change was experience by the control group (11.9 ± 3.2 to 12.6 ± 3.8 kJ), with no significant change in CP for either group.

The relationship between W' and the outcomes of these training studies, association with tests of anaerobic power and capacity, and the overall lack of change under hypoxic conditions (Dekerle et al., 2012; Simpson et al., 2015) strongly suggests that the W' is anaerobic in nature. This does not however indicate to what degree each of the two anaerobic energy systems contribute to the W', or how reconstitution of ATP and metabolite clearance by the aerobic system may play a role in the continued activation of these systems. The aerobic system has rarely been considered as playing a role in the composition of the W', however, the $\dot{V}O_{2max}$ has been related positively to the W', recovery of W' during exercise below CP, and the magnitude of the slow component (Chorley, Bott, Marwood, & Lamb, 2020), indicating a role of the aerobic system in maintaining severe intensity exercise performance.

With regards to the alactic component where intramuscular stores of ATP and PCr are utilised, supplementation of creatine monohydrate (20g/d for 5d) has been demonstrated to significantly increase W' (10.9 ± 2.7 to 13.7 + 3.0 kJ, $p<0.05$), with a positive effect being noticed in all participants, without affecting CP (Miura et al., 1999). This was subsequently supported (Eckerson, Stout, Moore, & Stone, 2005) and explained via the resultant increase in PCr stores boosting anaerobic capacity. Additionally, PCr also has a role as a proton buffer (Smith, Stephens, Hall, Jackson, & Earnest, 1998). This occurs by utilising the adenosine diphosphate and H+ generated by the breakdown of ATP, which assists in maintaining muscle cell homeostasis. It is therefore important to consider the role the ability to maintain homeostasis within the muscle may have on the magnitude on the W' rather than just the capacity of the energy systems.

It appears the capacity of the ATP-PCr system plays a significant role in determining the magnitude of the W'. However, the ATP-PCr system makes up a comparatively small proportion of the energy provision during endurance cycling, while anaerobic glycolysis is the more predominant anaerobic system (Craig & Norton, 2001; Jeukendrup et al., 2000). The glycolytic capacity may therefore be one of the largest contributing factors to the W'. The glycolytic process results in the rapid net gain of two ATP as well as the production of two pyruvate molecules which can utilised in the Krebs cycle to generate ATP if oxygen is available. Alternatively, each pyruvate can take up one H^+ to form two lactate molecules, which can then be converted back to pyruvate and combusted in the Krebs cycle when oxygen becomes available (Sahlin, 2014). The accumulation of H^+ lowers the pH of the muscle, inhibiting glycolytic enzymes such as phosphofructokinase (Wells et al., 2009). This inhibits the ability to generate ATP through anaerobic glycolysis, as well as the ability to provide pyruvate for later aerobic combustion, diminishing the ability to work in the severe intensity domain. The ability to perform glycolysis is limited by the maximum acidosis that can be tolerated by the muscle cell and the ability to form lactate as a buffer (Heck, Schulz, & Bartmus, 2003). Both these abilities are directly linked to the maximal glycolytic capacity (Heck et al., 2003; Mader & Heck, 1986) and are critical in limiting muscle perturbation, therefore allowing continued work in the severe intensity domain.

A greater glycolytic capacity therefore should result in a greater ability to maintain homeostasis in the muscle and allow continued activation of glycolysis and oxidative phosphorylation (Jubrias, Crowther, Shankland, Gronka, & Conley, 2003). This may facilitate an enhanced work capacity in the severe exercise domain and therefore greater W'. Given the role of the glycolytic capacity in producing ATP quickly, forming lactate as an H^+ buffer, and as the predominant anaerobic system in endurance cycling (Craig & Norton, 2001; Jeukendrup et al., 2000), it seems likely that the glycolytic capacity may play a significant role in determining the magnitude of the W'. The role of the glycolytic capacity in the magnitude of the W' is therefore worthy of investigation alongside other bioenergetic variables relating to the CP and W'.

Chapter 3: Research Aims and Hypothesis

Factors influencing the CP and W' have been well identified through a multitude of research, yet information regarding the energetic composition of the Critical Power model is limited. Previous work has focussed on the physiological aspects related to the CP with little regard for the physiological components of the W'. Therefore, the aim of this study was:

To investigate the determinants of Critical Power and W' through measures of bioenergetics in elite endurance cyclists.

It is hypothesised that measures associated with anaerobic pathways (Peak power, $\dot{V}La_{max}$) will better predict W' and the work capability above CP. While those associated with aerobic metabolism (W_{max}, $\dot{V}O_{2max}$, VT^1 and VT^2 power outputs) will better predict CP.

Alternatively, it is hypothesised that both measures of anaerobic and aerobic capability significantly contribute to both W' and CP aspects of the critical power model.

A secondary aim of this research was to investigate the relationship between the $\dot{V}La_{max}$ and supramaximal/extreme intensity exercise, as well as compare the differences in the CP and W' parameters calculated from four different Critical Power modelling methods.

Chapter 4: Methods

4.1 Participants and design

Ten elite, nationally and internationally competitive endurance male cyclists (3-15 years racing/training experience, age = 25 ± 5 years; height = 178.7 ± 3.5 cm; weight = 70.3 ± 7.7 kg; $\dot{V}O_{2max}$ = 71.9 ± 5.9 $ml \cdot kg^{-1} \cdot min^{-1}$) with previous experience of critical power testing volunteered to participate in three testing sessions, separated by at least 24-h, but limited to a three week period. Participants were training 400-800km/wk. with all but one cyclist currently in the process of training for events at national or international level. Two of the cyclists had competed at the 2018 Commonwealth games on the track, including one winning a gold medal, while the other also competed in the 2016 Olympic road race. One participant completed the first testing session before withdrawing due to a muscular injury unrelated to the study. The participants results from the $\dot{V}O_{2max}$ test, $\dot{V}La_{max}$ test, and one-minute time trial (TT) were used in the analysis, but CP and W' values were not able to be determined as the four and ten minute tests were not completed.

All participants viewed the study information sheet (Appendix 1) and were fully informed of the aims, experimental protocols, requirements, and the risks and benefits of the research. All participants completed a pre-exercise health questionnaire (Appendix 2) and provided written informed consent (Appendix 3). Participants were to be excluded if the lead researcher deemed answers to the questionnaire indicated taking part in the study could pose a significant risk to participants health. The research procedures were approved by the Massey University Human Ethics Committee, Southern A, Application 20/42.

Prior to each of the three testing sessions participants were instructed to continue their usual dietary habits as per training and racing in the case of the time trials, but were asked not to partake in strenuous exercise outside of the study trials for 24-h prior, or to consume caffeine two hours prior to testing session one ($\dot{V}La_{max}$, $\dot{V}O_{2max}$, and one-minute TT) as this has been shown to change the lactate response (Anselme, Collomp, Mercier, Ahmaidi, & Prefaut, 1992; Collomp, Ahmaidi, Audran, Chanal, & Prefaut, 1991).

4.2 Experimental trials

Upon arrival at the laboratory for the first session participants body weight (kg) and height (cm) were recorded using a set of scales (SECA 876, Hamburg, Germany) and a stadiometer (SECA 213, Hamburg, Germany).

All of the cycling tests were performed in a seated position on the participants own bikes attached to one of three 'smart trainers' (Wahoo KICKR, Wahoo Fitness, Atlanta, GA, USA; Elite Suito, Fontaniva, Italy; and Tacx Neo Smart T2800, Wassenaar, Netherlands) with the exception of the $\dot{V}La_{max}$ test which used the Cyclus 2 ergometer (Avantronic, Leipzig, Germany). The need to use multiple trainers arose due to bike compatibility restrictions on the different trainers currently available. The trainers were calibrated according to the manufacturers guidelines prior to each use. Seven participants completed testing on the Wahoo KICKR, two on the Elite Suito, and one on the Tacx Neo. All participants completed their three TT's on the same smart trainer.

The Wahoo KICKR has demonstrated good accuracy and reliability of power measurements in previous studies (Hoon, Michael, Patton, Chapman, & Areta, 2016; Zadow, Kitic, Wu, & Fell, 2018; Zadow, Kitic, Wu, Smith, & Fell, 2016). All trainers were compared to the Verve Infocrank (InfoCrank Classic, Verve Cycling, Perth, Australia) which is validated as accurate and reliable (Maier, Schmid, Müller, Steiner, & Wehrlin, 2017). The mean coefficient of variation (CV) was 0.64% between the Tacx Neo and the Infocrank, 0.49% between the Wahoo KICKR and the Infocrank, and 1.64% between the Elite Suito and the Infocrank. All power meters were determined to be within acceptable levels of agreement (Hopkins, Marshall, Batterham, & Hanin, 2009; Hopkins, 2000). Details of the analysis are presented in Appendix 4.

4.3 Session 1

Within this testing session participants completed three different testing protocols including the glycolytic capacity test ($\dot{V}La_{max}$ test), a one-minute all-out time trial (TT) and a graded ramp test to exhaustion ($\dot{V}O_{2max}$ test). The session is graphically represented in figure 4.

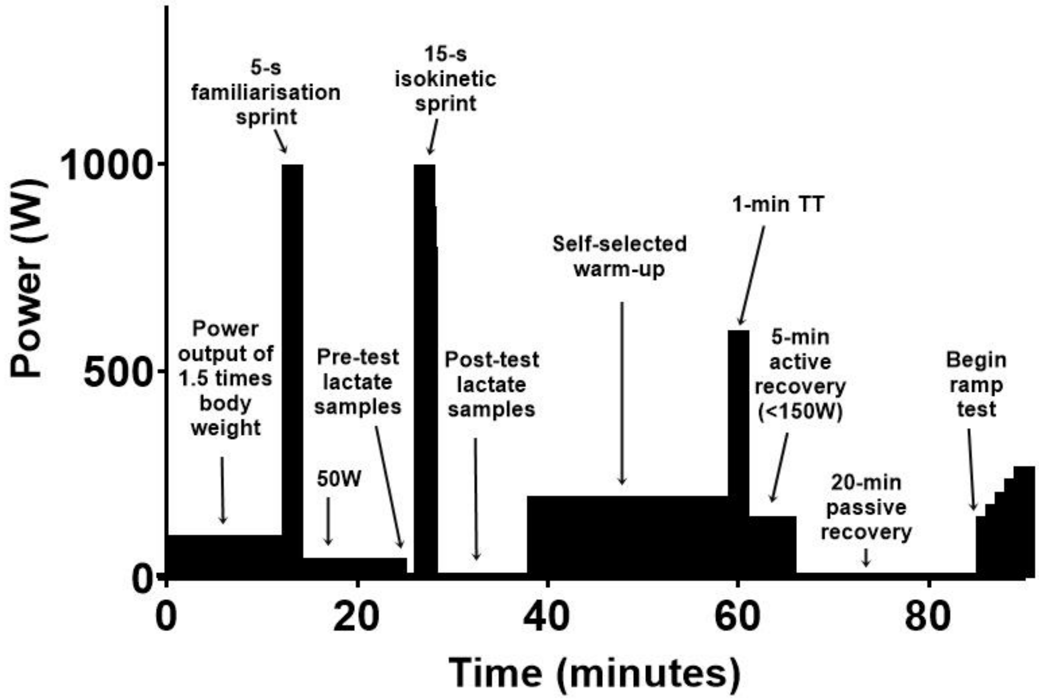

Figure 4. Graphical representation of the session 1 protocol.

$\dot{V}La_{max}$ test

Following a standardised warm-up (Adam et al., 2015; Hauser et al., 2014) including 12-min cycling at a power output (W) of 1.5x body weight, followed by a five second all-out sprint at 130 rpm (isokinetic mode), and a further ten minutes of cycling at a power output of 50W participants completed the $\dot{V}La_{max}$ test. This test was performed on participants own bikes fitted to a Cyclus 2 ergometer (Avantronic, Leipzig, Germany).

Immediately post warm-up two capillary lactate samples were taken from a sterilised earlobe using the lactate scout 4 (EKF Diagnostic, GmbH, Barleben, Germany) to establish the pre-test lactate concentration (La_{Pre}). Following La_{Pre} collection the ergometer was set to isokinetic mode (130 rpm) and participants were given a five second countdown preceding the 15-s (t_{test}) all-out effort. Power output (W) was logged at 8-Hz in order to record initial peak power (PP) and the time to reach PP minus 3.5% (t_{alac}) which signifies the alactic component of the test. Additionally, Test End Power (mean power over the last 2-s) was recorded representing energy contribution from glycolytic metabolism (Gastin, 2001; Wells et al., 2009) with a low aerobic contribution due to the delay of the $\dot{V}O_2$ kinetics (Bailey, Vanhatalo, Wilkerson, DiMenna, & Jones, 2009; Burnley & Jones, 2007). A valid $\dot{V}La_{max}$ test is confirmed by a gradual work rate decline after the initial PP was achieved (Figure 5).

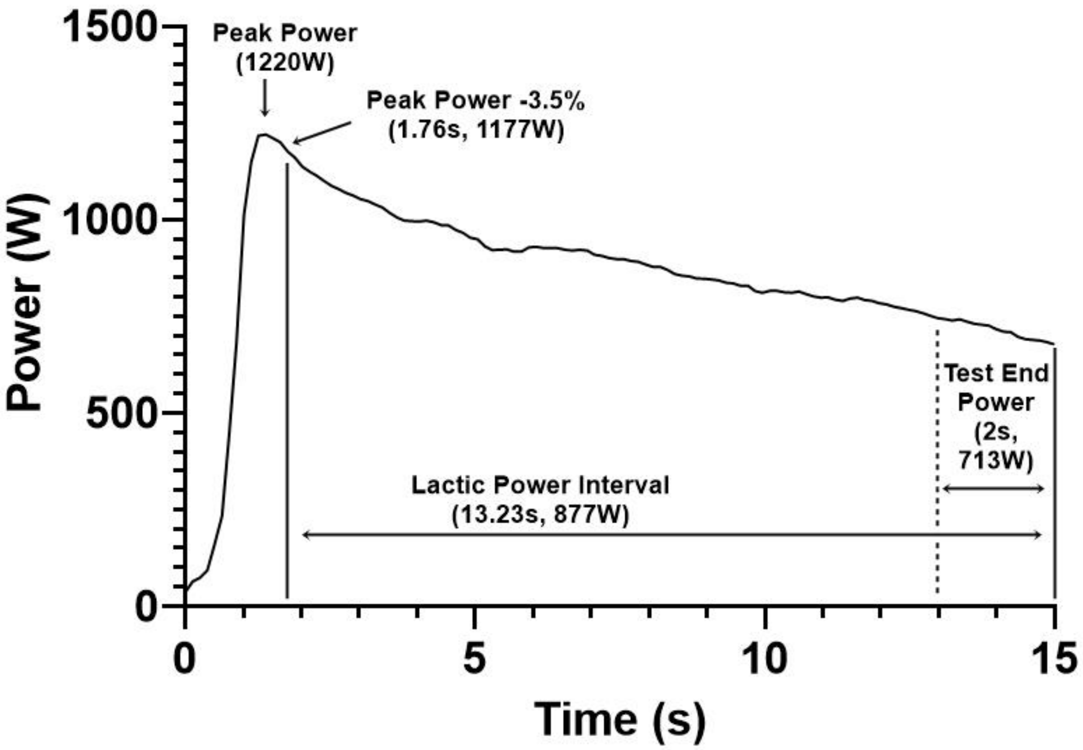

Figure 5. Example of a valid $\dot{V}La_{max}$ test. After peak power the power output gradually declines without any notable increase. There is no notable decrease in power indicating the participant exerted maximum effort right to the end of the test.

At the completion of the 15-s sprint participants were instructed to stop pedalling and remain stationary whereupon lactate samples were taken immediately post-test, and every minute thereafter until a decline occurred and maximum lactate concentration was recorded ($La_{maxPost}$). The $\dot{V}La_{max}$ ($mmol \cdot L^{-1} \cdot s^{-1}$) is calculated according to equation 1 and is used to infer the glycolytic capacity (Adam et al., 2015; Hauser et al., 2014; Nitzsche, Baumgärtel, Maiwald, & Schulz, 2018).

$$\dot{V}La_{max} = \frac{La_{maxPost} - La_{Pre}}{t_{test} - t_{alac}}$$

Equation 1. Where, $\dot{V}La_{max}$ = Maximal lactate production rate, $La_{maxPost}$ = maximal lactate post-test lactate concentration, La_{Pre} = Pre-test lactate concentration, t_{test} = test duration (15s), t_{alac} = alactic time duration. The alactic time was defined as the time from the start of the test until maximum power has declined by 3.5%

1-Minute Time Trial

Following the $\dot{V}La_{max}$ test the participants bike was transferred off the Cyclus 2 ergometer and onto the smart trainer. The 1-min TT required participants to ride as hard (self-selected pacing strategy) as possible for a 1-min period to obtain the best average power. Power data was logged at 1-Hz throughout the test using a Garmin Edge 530 (Garmin, Schaffhausen, Switzerland). The 1-min TT was preceded by a self-selected warm-up routine which had been approved by the researcher as a valid warm-up before commencement of the study. The test was initiated from a low power output (<200W) and cadence of 70-80rpm.

Familiarisation was not undertaken as all participants had significant experience training with power meters and performing critical power testing.

Preceding the $\dot{V}O_{2max}$ test and following the 1-min TT participants completed 5-min of active recovery (<150 W), followed by 20-min of passive recovery. Active recovery at low intensities has been shown to return blood lactate concentrations towards baseline faster than passive recovery (Monedero & Donne, 2000), while passive recovery may allow greater restoration of PCr in the muscle and greater subsequent performance in high intensity exercise (Buchheit et al., 2009; Spencer, Bishop, Dawson, Goodman, & Duffield, 2006). Therefore, these two recovery methods were combined.

$\dot{V}O_{2max}$ test

The $\dot{V}O_{2max}$ test commenced at a work-rate of 150W, with a ramped 30 $W \cdot min^{-1}$ increase until volitional exhaustion. Gas exchange data was collected via a ParvoMedics Trueone 2400 metabolic system (ParvoMedics, Salt Lake City, UT, USA) and averaged every 15-s. Attainment of $\dot{V}O_{2max}$ was defined from the most common methods of determining $\dot{V}O_{2max}$ from a review of the literature by Midgley, McNaughton, Polman, and Marchant (2007); RER ≥ 1.10; heart rate reaching within 10bpm of known maximum (determined from training data); and a plateau in $\dot{V}O_2$ of less than 150ml in the final minute of the test. $\dot{V}O_{2max}$ was determined as the highest 1-min average $\dot{V}O_2$ across the test. A re-test was required if the heart rate and RER criteria were not met.

Submaximal ventilatory thresholds (VT_1 and VT_2) were subsequently calculated where VT_1 coincided with an increase in both $\dot{V}E \cdot \dot{V}O_2^{-1}$ (ventilatory equivalents for oxygen) and $P_{ET}O_2$ (end-tidal partial pressure of oxygen) and no corresponding increase in $\dot{V}E \cdot \dot{V}CO_2^{-1}$ (ventilatory equivalents for carbon dioxide). VT_2 coincided with an increase in $\dot{V}E \cdot \dot{V}O_2^{-1}$ and $\dot{V}E \cdot \dot{V}CO_2^{-1}$ with a corresponding decrease in $P_{ET}CO_2$ (end-tidal partial pressure of carbon dioxide) (Lucía, Hoyos, Pérez, & Chicharro, 2000).

4.4 Session 2-3

The aim of testing sessions 2 and 3 were to obtain the best (self-selected pacing strategy) over a 4 and 10-min period separated by at least 24-h (Bishop & Jenkins, 1995; Karsten, Hopker, et al., 2017) to determine CP and W' using the linear-TW model (Moritani et al., 1981). The order of the 4 and 10-min tests was randomised, however, participants were advised 24-h pre visit so they could prepare mentally for the effort.

As these tests are performance orientated participants were encouraged to use their normal warm-up routines prior to a short duration time trial. However, this routine had to be approved by the lead researcher prior to each test session.

As per the 1-min TT each test duration was initiated from a low power output (<200W) and cadence of 70-80rpm. Once the test commenced participants remained seated and received verbal encouragement throughout. Power output logged (1 Hz) throughout each test using a Garmin Edge 530, was averaged, converted to total work completed (kJ), plotted against the duration of the trial (Figure 3-A) and analysed using linear regression. The slope of the regression line was deemed as the CP while the y-intercept was deemed as the W' (Bergstrom et al., 2014; Bull et al., 2000).

The linear-TW model has been used in past research on elite level cyclists (Bartram et al., 2017), and is prevalent within the literature (Dekerle et al., 2003; Jenkins & Quigley, 1990; Simpson et al., 2015). The use of just 2 efforts has been found to result in accurate CP results as long as the tests differ by at least 5-min in duration and are longer than 1-min (Housh et al., 1990).

4.5 Analysis of Data

The 1-min TT effort was not used in the primary analysis of CP and W’ as short efforts have been found to be both poorly predicted by linear CP models and deviate from the otherwise linear time-work relationship (Vandewalle et al., 1997; Vinetti et al., 2019).

The 1-min effort was rather used to determine if $\dot{V}La_{max}$ was related to extreme intensity exercise performance. TT’s were used as opposed to time to exhaustion tests as these have been shown to result in accurate CP estimates (Karsten, Baker, et al., 2017; Triska et al., 2017) and are commonly conducted by elite cyclists during testing. W’ estimates derived from TT’s are also accurate and reliable as long as participants are familiar with CP testing. This avoided the need to estimate appropriate power outputs for each participant for time to exhaustion trials, which would also result in different effort durations for each participant. A minimum of 24-h was chosen between TT efforts as this has been shown to provide the most accurate and reliable CP and W’ estimates (Bishop & Jenkins, 1995; Karsten, Hopker, et al., 2017).

The four and ten-minute TT’s and the linear-TW model were used to calculate all CP and W’ estimates, except where different CP models were being compared. In this case the 1, 4, and 10-min tests were used to calculate CP and W’ for all 4 models as a minimum of three efforts are needed to form the hyperbolic models. P_{max} for the Hyp-3P model was taken as the maximum power in the $\dot{V}La_{max}$ test. All models were calculated according to the formulas in Table 1.

The work completed above CP in the 1-min TT was calculated by subtracting the CP from the 1-min TT power multiplied by the test duration in seconds (60s).

4.6 Statistical Analysis

Data is reported as mean ± standard deviation (SD) unless otherwise stated.

Pearson’s correlation coefficient (r and r^2) was used to analyse the relationships between physiological variables and test power outputs with CP and W’. Multiple regression was used to analyse the predictive power of variables on an output measure. PP, $\dot{V}La_{max}$, and $\dot{V}O_{2max}$, CP, and W’ were used in this analysis. These measures were chosen as representative measures of the maximum capacity of the ATP-PCr, glycolytic, and aerobic system respectively, along with CP as a measure of the highest steady-state intensity, and W’ as the work capacity above this intensity. As the most strongly correlated variable with $\dot{V}La_{max}$, the lactic interval power was used in a linear regression in order to compare predicted and measured $\dot{V}La_{max}$.

The difference in W’ depleted in the 1-min effort was compared to the W’ derived from the four and ten-minute TT’s. VT_2 and CP were also compared for differences. These were tested for significance using a two-tailed, paired, students t-test.

One-way ANOVA was used to analyse the difference between the different models for CP, VT_2 and W’, while Šidák’s multiple comparison correction was used to test significance between individual models. The data was tested for sphericity which was not violated.

All statistical analysis was done in Statistical Package for Social Sciences (SPSS, version 23, IBM, New York, USA), with a priori statistical significance set as $p<0.05$. SPSS was used to calculate the hyperbolic models, with the CP and W’ derived from the linear-TW model used as the starting point for the derivations.

Chapter 5: Results

The mean ± SD (range) for variables representing the maximum capacity of the ATP-PCr, glycolytic, and aerobic systems respectively were 1272 ± 309 (974-2040) W (17.9 ± 2.6, 14.2-22.6 $W \cdot kg^{-1}$) for PP, 0.51 ± 0.13 (0.36-0.74) $mmol \cdot L^{-1} \cdot s^{-1}$ for $\dot{V}La_{max}$, and 70.1 ± 5.9 (60.0-79.1) $ml \cdot min^{-}1 \cdot kg^{-1}$ (4.91 ± 0.44, 4.25-5.65 $L \cdot min^{-1}$) for $\dot{V}O_{2max}$, respectively.

Time-trial test, mean ± SD (range) including $\dot{V}La_{max}$, one, four, and ten minute tests, for all participants were 876 ± 196 (707-1374) W, 575 ± 73 (506-735) W, 412 ± 43 (360-481) W, and 361 ± 40 (308-428) W, respectively. Data from the 4 and 10-min tests (Figure 6A-B) were used to calculate CP (327 ± 41, 263-393 W) and W' (20.5 ± 5.4, 12.7-28.1 kJ). Data from the graded exercise test included mean ± SD (range) W_{max} (415 ± 52 (347-512) W), VT_1 (264 ± 28 (240-300) W), and VT_2 (330 ± 35 (270-390) W).

D'Agostino and Pearson's normality test showed all data sets passed the test with p-values >0.05, except for mean power in the $\dot{V}La_{max}$ test (p=0.0006) (Appendix 5).

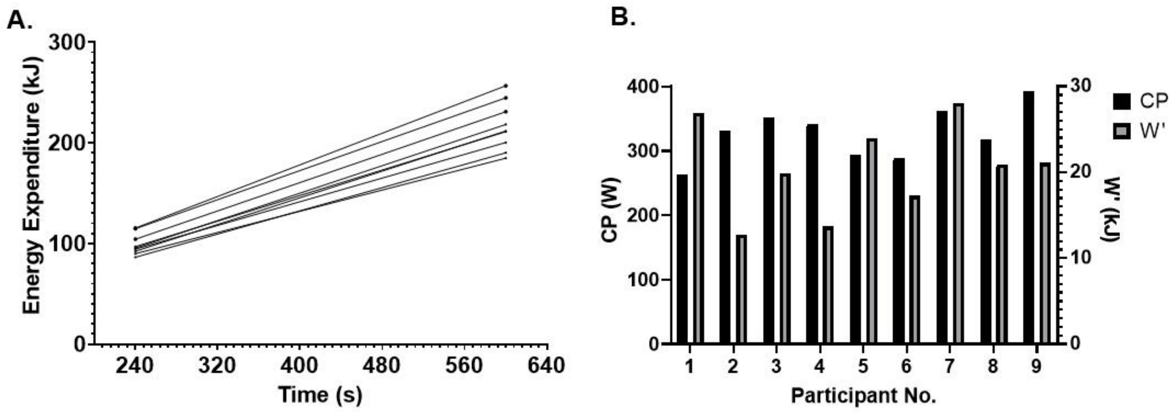

Figure 6. A: Linear Time-Work plot of participants TT efforts. **B:** CP and W' values for all participants.

5.1 $\dot{V}La_{max}$ test

Peak lactate from the $\dot{V}La_{max}$ test was 8.0 ± 1.9 (5.9-11.7) $mmol \cdot L \cdot s^{-1}$ which occurred 3.5 ± 1.6 (2-6) minutes after the conclusion of the isokinetic sprint. Time to PP was 1.21 ± 0.22 (0.88-1.51) seconds, with time to PP minus 3.5% occurring at 1.58 ± 0.27s (1.26-2.02s). After reaching PP all participants displayed a gradual decline in power until the end of the test with no notable increase or large drop off in power (Figure 7). Mean $\dot{V}La_{max}$ was 0.51 ± 0.13 (0.36-0.74) $mmol \cdot L \cdot s^{-1}$.

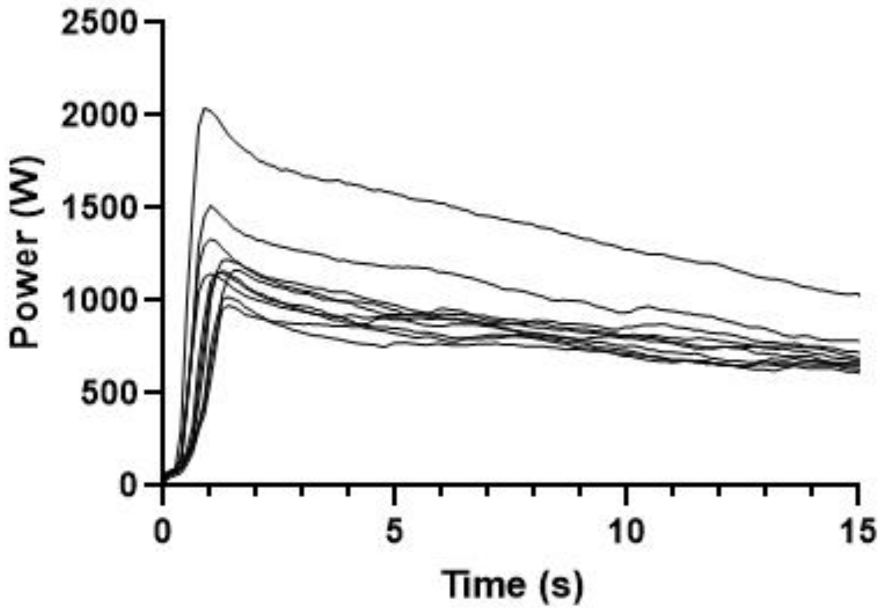

Figure 7. Individual participant power-time plot during the $\dot{V}La_{max}$ test

Mean power during the test was 876 ± 196 (707-1374)W, power over the lactic interval of the test was 902 ± 196 (734-1399)W, and test end power was 735 ± 127 (634-1067) W. Power over the lactic interval displayed the strongest relationship with $\dot{V}La_{max}$ (r=0.80, r^2=0.65, p=0.005), followed by mean test power (r=0.79, r^2=0.62, p=0.007), and test end power (r=0.75, r^2=0.56, p=0.012). Relative ($W \cdot kg^{-1}$) power outputs were 12.38 ± 1.62 (9.85-15.22) $W \cdot kg^{-1}$ for mean test power, 12.75 ± 1.62 (10.22-15.49) $W \cdot kg^{-1}$ for power over the lactic interval, 10.42 ± 0.87 (8.83-11.82) $W \cdot kg^{-1}$ for test end power. Relative power over the lactic interval displayed the strongest relationship with $\dot{V}La_{max}$ (r=0.87, r^2=0.75, p=0.0011), followed by relative mean test power (r=0.85, r^2=0.72, p=0.0017), and relative test end power (r=0.83, r^2=0.68, p=0.0034). For absolute power variables, power over the lactic interval displayed the lowest absolute and percentage standard error in predicting $\dot{V}La_{max}$ (0.08 $mmol \cdot L \cdot s^{-1}$, 15.69%), followed by mean test power (0.08 $mmol \cdot L \cdot s^{-1}$, 16.27%), and test end power (0.09 $mmol \cdot L \cdot s^{-1}$, 17.30%), while for relative measures power over the lactic interval also displayed the lowest absolute and percentage error (0.07 $mmol \cdot L \cdot s^{-1}$, 13.11%), followed by mean test power (0.07 $mmol \cdot L \cdot s^{-1}$, 13.80%), and test end power (0.08 $mmol \cdot L \cdot s^{-1}$, 15.00%). As the variable most strongly correlated with $\dot{V}La_{max}$, power over the lactic interval of the test was used to form a linear regression equation to predict $\dot{V}La_{max}$ for both absolute (Figure 8-A) ($F_{(1, 7)}$, p=0.011, r^2=0.624, adjusted r^2=0.571) and relative power outputs (Figure 8-B) ($F_{(1, 7)}$, p=0.004, r^2=0.714, adjusted r^2=0.673). The table of coefficients are presented in tables 2 and 3.

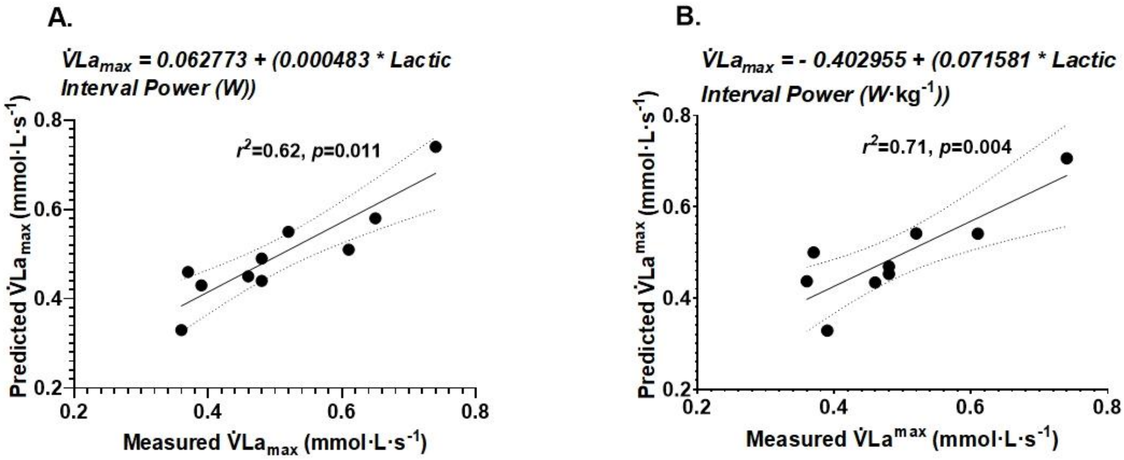

Figure 8. A: Predicted vs measured V̇La$_{max}$ from lactic interval power. **B:** Predicted vs measured V̇La$_{max}$ from lactic interval power (W·kg^{-1}).

Table 2. Table of coefficients for prediction of V̇La$_{max}$ from Lactic Interval Power (W)

	Unstandardised Coefficients		**Standardised Coefficients**			**95.0% Confidence Interval for B**	
Model	B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound
(Constant)	0.062773	0.128		0.490	0.639	-0.240	0.366
Lactic Interval Power (W)	0.000483	0.0001	0.790	3.410	0.011	0.0001	0.001

Table 3. Table of coefficients for prediction of V̇La$_{max}$ from Lactic Interval Power (W·kg^{-1})

	Unstandardised Coefficients		**Standardised Coefficients**			**95.0% Confidence Interval for B**	
Model	B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound
(Constant)	-0.402955	0.215		-1.874	0.103	-0.911	0.105
Lactic Interval Power (W·kg^{-1})	0.071581	0.017	0.845	4.178	0.004	0.031	0.112

5.2 Relationships between Bioenergetic variables, CP and W'

All relationships are presented in Table 4. Key relationships identified for aerobic variables relating to the main hypothesis were between $\dot{V}O_{2max}$ (L·min^{-1}) and CP (W) (r=0.91, r^2=0.83, p=0.0007), $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}) and CP (W·kg^{-1}) (r=0.89, r^2=0.79, p=0.0014), W_{max} and CP (r=0.92, r^2=0.84, p=0.0005), CP and VT_1 (r=0.72, r^2=0.52, p=0.028), and CP and VT_2 (r=0.85, r^2=0.73, p=0.0035). Despite the strongest relationship being between W_{max} and CP, Šidák's post-hoc multiple comparisons test revealed significant differences between these two power outputs for the nine participants who completed the study (414 ± 55 vs 326 ± 41 W, p<0.0001), however, neither power at CP and VT_2 (327 ± 41 vs 330 ± 37 W, p=0.91), or W·kg^{-1} at CP and VT_2 (4.66 ± 0.54 vs 4.72 ± 0.58 W·kg^{-1}, p=0.95) were significantly different.

The only variables to display a significant relationship with W' were $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}) (r=-0.67, r^2=0.45, p=0.047) (Figure 9-A), and CP (W·kg^{-1}) (r=-0.69, r^2=0.47, p=0.042) (Figure 9-B). The relationship between W' and $\dot{V}La_{max}$ approached, but did not reach, statistical significance (r=0.66, r^2=0.44, p=0.051), as did the relationship between body mass (kg) and W' (r=0.57, r^2=0.33, p=0.11).

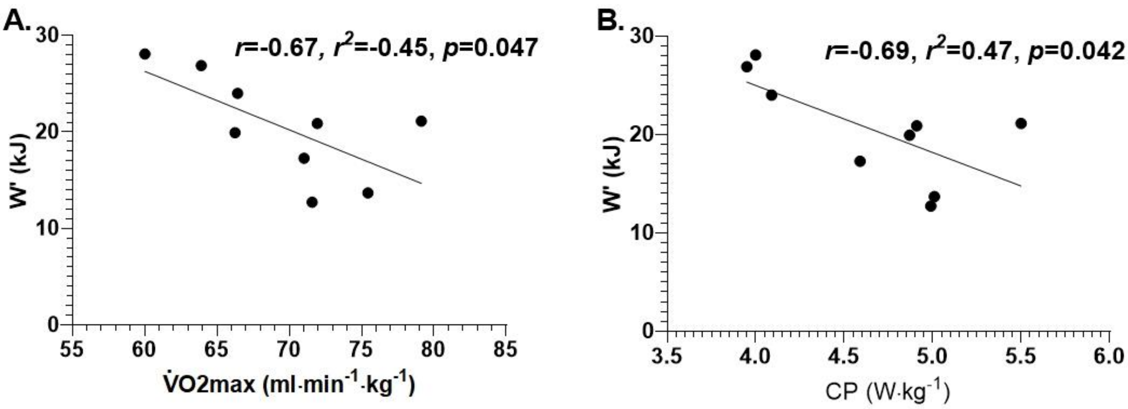

Figure 9: A: Relationship between W' and $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}) **B:** Relationship between W' and CP (W·kg^{-1})

Table 4. Correlation matrix of variables displaying Pearson's correlation coefficient between variables

	Peak Power (W)	**Peak Power ($W \cdot kg^{-1}$)**	**$\dot{V}La_{max}$ ($mmol \cdot L^{-1} \cdot s^{-1}$)**	**$\dot{V}La_{max}$ end power (W)**	**$\dot{V}La_{max}$ end power ($W \cdot kg^{-1}$)**	**W' (kJ)**	**CP (W)**	**CP ($W \cdot kg^{-1}$)**	**W_{max} (W)**	**$\dot{V}O_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)**	**$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)**	**VT_1**	**VT_2**
Peak Power (W)		0.901**	0.750*	0.974***	0.773*	0.531	0.407	-0.371	0.396	-0.469	0.490		0.062
Peak Power ($W \cdot kg^{-1}$)	0.901**		0.786*	0.825*	0.893**	0.423	0.291	0.296	0.189	-0.282	0.331	0.203	-0.088
$\dot{V}Lamax$ ($mmol \cdot L^{-1} \cdot s^{-1}$)	0.750*	0.786*		0.751*	0.824*	0.665	-0.039	-0.534	0.016	-0.301	0.238	-0.266	-0.435
$\dot{V}La_{max}$ end power (W)	0.974***	0.825*	0.751*		0.780*	0.591	0.425	-0.358	0.422	-0.480	0.513	0.259	0.084
$\dot{V}La_{max}$ end power ($W \cdot kg^{-1}$)	0.773*	0.893**	0.824*	0.780*		0.454	0.198	-0.218	0.061	-0.202	0.240	0.166	-0.181
W' (kJ)	0.531	0.423	0.665	0.591	0.454		-0.145	-0.685*	0.047	-0.674*	0.040	-0.191	-0.325
CP (W)	0.407	0.291	-0.039	0.425	0.198	-0.145		0.626	0.915**	0.364	0.910***	0.722*	0.853*
CP ($W \cdot kg^{-1}$)	0.407	0.296	0.534	-0.358	-0.218	-0.685*	0.626		0.427	0.887*	0.938***	0.629	0.840*
W_{max}(W)	0.396	0.189	0.016	0.422	0.061	0.047	0.915**	0.427		0.275	0.938***	0.629	0.840*
$\dot{V}O_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	-0.469	-0.282	-0.301	-0.480	-0.202	-0.674*	0.364	0.887*	0.275		0.359	0.173	0.411
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	0.490	0.331	0.238	0.513	0.240	0.040	0.910***	0.414	0.938***	0.359		0.489	0.715*
VT_1	0.246	0.203	-0.266	0.259	0.166	-0.191	0.722*	0.508	0.629	0.173	0.489		0.838*
VT_2	0.062	-0.088	-0.435	0.084	-0.181	-0.325	0.853*	0.657	0.840*	0.411	0.715*	0.838*	

*Where * signifies $p<0.05$, ** $p<0.001$, *** $p<0.0001$*

A multiple regression was run to predict CP and W’ from variables reflecting energy systems capability. CP (W·kg^{-1}) was significantly predicted ($F_{(4, 4)}$ =44.470, p=0.001, r^2=0.978, adjusted r^2=0.956, Figure 10-A, Table 5) by relative bioenergetic variables and work capacity above CP (PP (W·kg^{-1}), $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}), $\dot{V}La_{max}$, and W’), however, absolute CP (W) was not significantly predicted ($F_{(4, 4)}$=5.597, p=0.062, r^2=0.848, adjusted r^2=0.697, Figure 10-B, Table 6) by the same absolute variables (PP (W), $\dot{V}O_{2max}$ (L·min^{-1}), $\dot{V}La_{max}$, and W’).

W’ was significantly predicted ($F_{(4, 4)}$ =8.054, p=0.034, r^2=0.890, adjusted r^2=0.779, Figure 10-C, Table 7) by relative bioenergetic variables (PP (W·kg^{-1}), $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}), $\dot{V}La_{max}$, and CP (W·kg^{-1})), however, W’ could not be significantly predicted ($F_{(4, 4)}$ =1.055, p=0.48, r^2=0.513, adjusted r^2=0.027, Figure 10-D, Table 8) by the same absolute variables (PP (W), $\dot{V}O_{2max}$ (L·min^{-1}), $\dot{V}La_{max}$, and CP (W)).

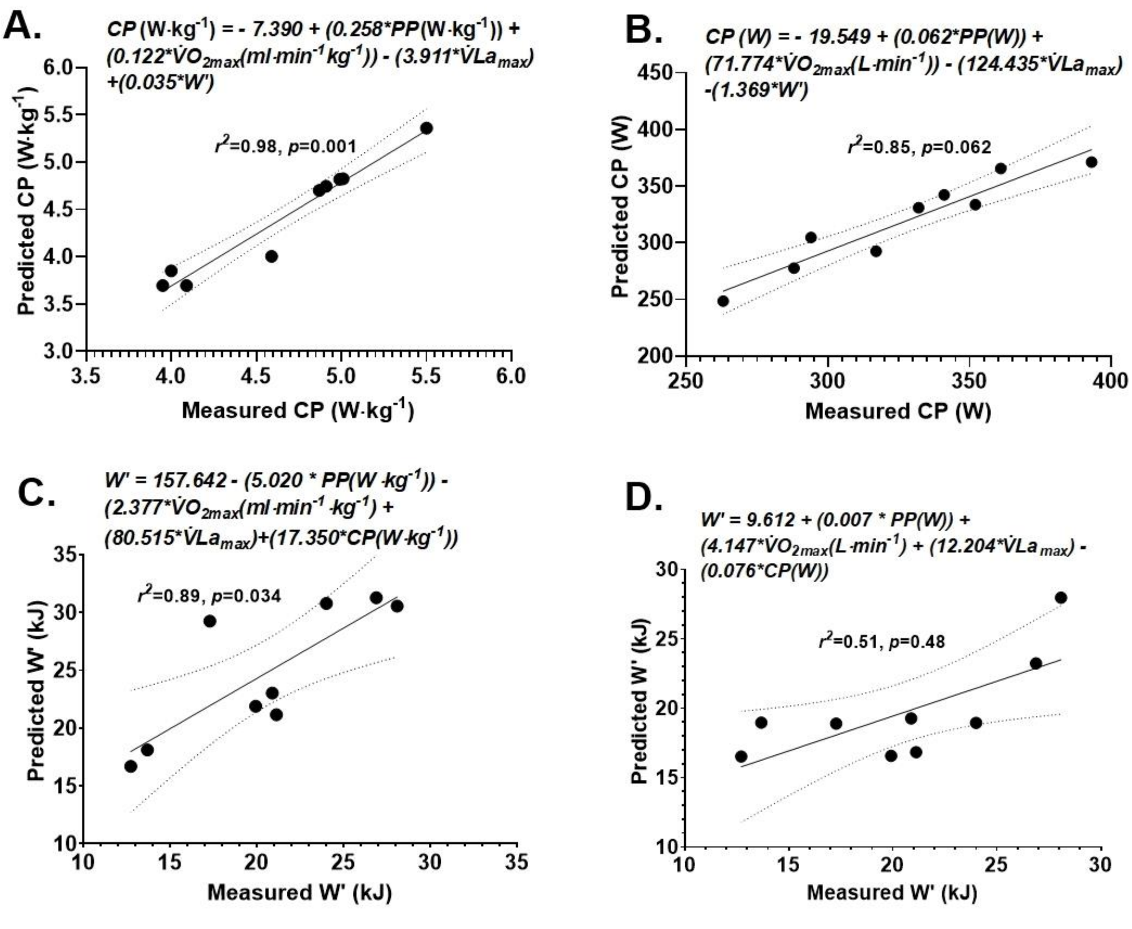

Figure 10. A: Predicted vs. measured CP (W·kg^{-1}) using PP (W·kg^{-1}), $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}), $\dot{V}La_{max}$, and W’. **B:** Predicted vs measured CP (W) using PP (W), $\dot{V}O_{2max}$ (L·min^{-1}), $\dot{V}La_{max}$, and W’. **C:** Predicted vs measured W’ using PP (W·kg^{-1}), $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}), $\dot{V}La_{max}$, and CP (W·kg^{-1}). **D:** Predicted vs measured W’ using PP (W), $\dot{V}O_{2max}$ (L·min^{-1}), $\dot{V}La_{max}$, and CP (W).

Table 5. Table of coefficients for CP (W·kg^{-1}) prediction derived from PP (W·kg^{-1}), $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}), $\dot{V}La_{max}$, and W’

	Unstandardised Coefficients		**Standardised Coefficients**			**95.0% Confidence Interval for B**	
Model	B	SE	Beta	t	Sig.	Lower Bound	Upper Bound
(Constant)	-7.390	1.441		-5.128	0.007	-11.392	-3.389
PP (W·kg^{-1})	0.258	0.035	1.136	7.384	0.002	-5.748	-2.075
$\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1})	0.122	0.013	1.345	9.437	0.001	0.086	0.158
$\dot{V}La_{max}$	-3.911	0.661	-0.892	-5.914	0.004	0.161	0.355
W’	0.035	0.014	0.347	2.482	0.068	-0.004	0.074

Table 6. Table of coefficients for CP (W) prediction derived from PP (W), $\dot{V}O_{2max}$ (L·min^{-1}), $\dot{V}La_{max}$, and W’

	Unstandardised Coefficients		**Standardised Coefficients**			**95.0% Confidence Interval for B**	
Model	B	SE	Beta	t	Sig.	Lower Bound	Upper Bound
(Constant)	-19.549	107.237		-0.182	0.864	-317.288	278.190
PP (W)	0.062	0.041	0.480	1.502	0.208	-0.052	0.176
$\dot{V}O_{2max}$ (L·min^{-1})	71.774	22.169	0.718	3.238	0.032	10.222	133.325
$\dot{V}La_{max}$	-124.435	108.011	-0.376	-1.152	0.313	-424.320	175.450
W’	-1.369	2.004	-0.180	-0.683	0.532	-6.931	4.194

Table 7. Table of coefficients for W’ prediction derived from PP (W·kg^{-1}), $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}), $\dot{V}La_{max}$, and CP (W·kg^{-1})

	Unstandardised Coefficients		**Standardised Coefficients**			**95.0% Confidence Interval for B**	
Model	B	SE	Beta	t	Sig.	Lower Bound	Upper Bound
(Constant)	157.642	39.981		3.943	0.017	46.638	268.647
PP (W·kg^{-1})	-5.020	1.606	-2.222	-3.126	0.035	-9.478	-0.561
$\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1})	-2.377	0.728	-2.627	-3.264	0.031	-4.399	-0.355
$\dot{V}La_{max}$	80.515	22.261	1.846	3.617	0.22	18.708	142.323
CP (W·kg^{-1})	17.350	6.991	1.745	2.482	0.068	-2.060	36.760

Table 8. Table of coefficients for W’ prediction derived from PP (W), $\dot{V}O_{2max}$ (L·min^{-1}), $\dot{V}La_{max}$, and CP (W)

	Unstandardised Coefficients		**Standardised Coefficients**			**95.0% Confidence Interval for B**	
Model	B	SE	Beta	t	Sig,	Lower Bound	Upper Bound
(Constant)	9.612	24.972		0.385	0.720	-59.722	78.945
PP (W)	0.007	0.012	0.433	0.635	0.560	-0.025	0.039
$\dot{V}O_{2max}$ (L·min^{-1})	4.147	9.744	0.315	0.426	0.692	-22.905	31.200
$\dot{V}La_{max}$	12.204	28.798	0.280	0.424	0.694	-67.752	92.159
CP (W)	-0.076	0.112	-0.579	-0.683	-0.532	-0.387	0.234

5.3 W' depletion during supramaximal exercise

Mean ± SD (range), 1-min TT power was 176 ± 21 (148-204) % of CP and 139 ± 15 (116-159) % of W_{max}. All participants displayed a positive pacing strategy where power decreased over the duration of the effort (Figure 11). 1-min TT power output (W) was significantly related to test end power (r=0.88, r^2=0.78, p=0.00065) and PP (r=0.85, r^2=0.73, p=0.0016), but not $\dot{V}La_{max}$ (r=0.43, r^2=0.18, p=0.22) or $\dot{V}O_{2max}$ ($L\cdot min^{-1}$) (r=0.55, r^2=0.31, p=0.10). Relative ($W\cdot kg^{-1}$) 1-min TT power was significantly related to test end power ($W\cdot kg^{-1}$) (r=0.79, r^2=0.62, p=0.0069), $\dot{V}La_{max}$ (r=0.85, r^2=0.73, p=0.0016) and PP ($W\cdot kg^{-1}$) (r=0.70, r^2=0.49, p=0.024), but not $\dot{V}O_{2max}$ ($ml\cdot min^{-1}\cdot kg^{-1}$) ($r$=0.48, r^2=0.23, p=0.16).

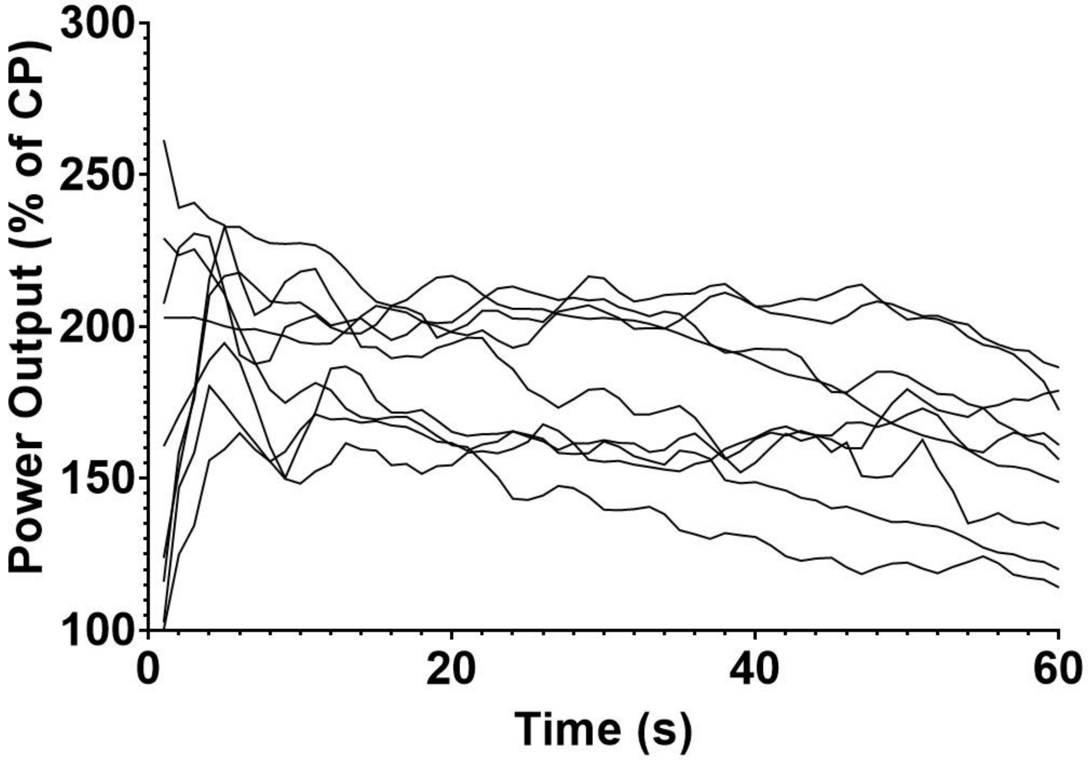

Figure 11: Individual Participant plot of 1-min TT power output relative to CP

Despite this extreme intensity combined with the duration, this effort was not sufficient for any participant to deplete their W' in the 1-min TT. A two-tailed, paired t-test revealed the work completed above CP was significantly less than the W' (14.7 ± 3.8 vs 20.5 ± 5.3kJ, p=0.0008, Figure 12). The amount of work completed above CP was strongly related to PP (r=0.78, r^2=0.61, p=0.01) but not $\dot{V}La_{max}$ (r=0.53, r^2=0.28, p=0.18).

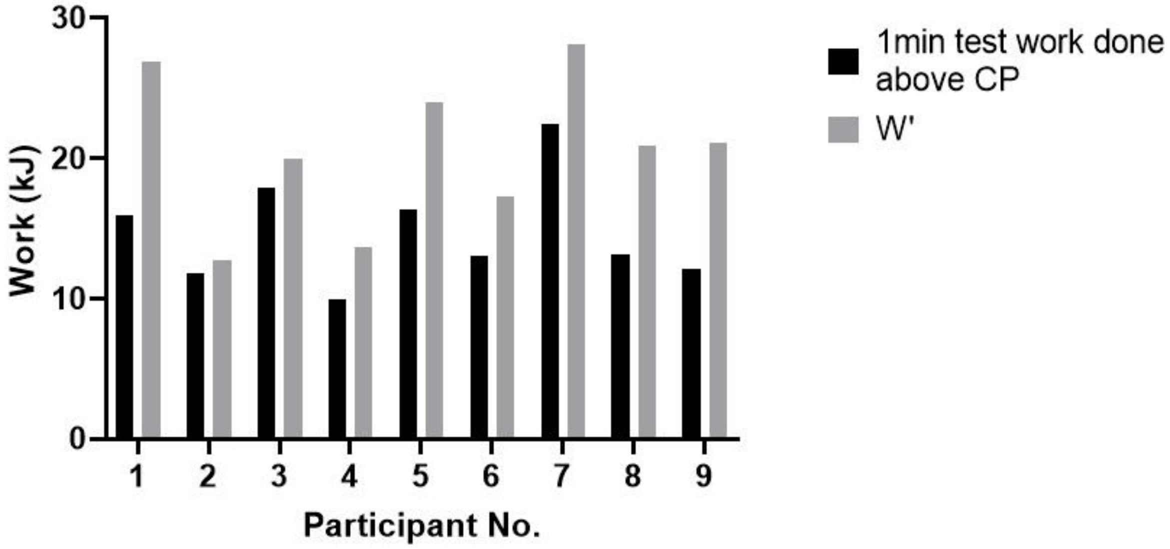

Figure 12. Comparison of work completed above CP in the 1-min TT and W' derived from 4 and 10-min TT's.

5.4 Differences Between Critical Power Models

One-way ANOVA revealed significant overall differences between models used to determine CP ($F_{(1.02,8.15)}$=32.13, p<0.001, Figure 13-A) and W' ($F_{(1.06,\ 8.49)}$=39.08, p<0.001, Figure 13-B). The linear-P model produced the highest CP estimates (346 ± 39W), followed by Linear-TW (336 ± 39W), Hyp-2P (329 ± 40W), and Hyp-3P (324 ± 41W). The opposite effect was true for W' with Linear-P producing the lowest estimate (13.67 ± 3.83 kJ), followed by Linear-TW (15.82 ± 3.95 kJ), Hyp-2P (19.05 ± 4.77 kJ), and Hyp-3P (23.15 ± 6.15 kJ). The mean coefficient of variation between models for CP was 2.9% (0.63-6.11)% and 22.8% (9.56-33.75)% for W'.

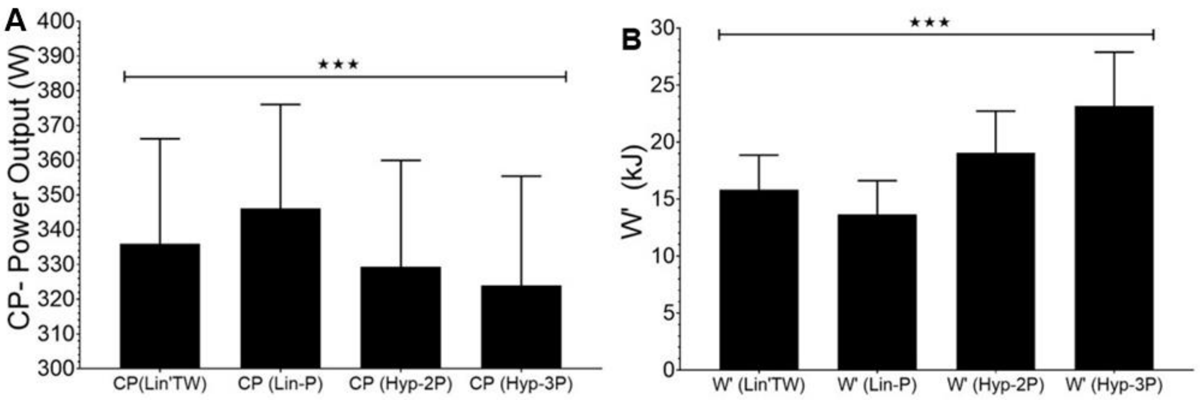

Figure 13. A: Comparison of CP between four different CP models. **B:** Comparison of W' between four different CP models. *** =ANOVA P<0.001

Šidák's post-hoc multiple comparisons revealed significant differences between each and every model for CP (Table 9) and W' (Table 10).

Table 9. Šidák's post-hoc multiple comparisons matrix for CP between models				
	Linear-TW	**Linear-P**	**Hyp-2P**	**Hyp-3P**
Linear-TW		*p*=0.0050, (-10.11W)	*p*=0.0035, (6.667W)	*p*=0.0014, (12.00W)
Linear-P	*p*=0.0050, (-10.11W)		*p*=0.0042, (16.78W)	*p*=0.0024, (22.11W)
Hyp-2P	*p*=0.0035, (6.667W)	*p*=0.0042, (16.78W)		*p*=0.0006, (5.333W)
Hyp-3P	*p*=0.0014, (12.00W)	*p*=0.0024, (22.11W)	*p*=0.0006, (5.333W)	
Numbers indicate *p*-value, (Mean difference (W)), after Šidák's post-hoc multiple comparisons analysis				

Table 10. Šidák's post-hoc multiple comparisons matrix for W' between models				
	Linear-TW	**Linear-P**	**Hyp-2P**	**Hyp-3P**
Linear-TW		*p*=0.005, (2.152kJ)	*p*=0.004, (-3.230kJ)	*p*=0.001, (-7.329kJ)
Linear-P	*p*=0.005, (2.152kJ)		*p*=0.004, (-5.382kJ)	*p*=0.002, (-9.481kJ)
Hyp-2P	*p*=0.004, (-3.230kJ)	*p*=0.004, (-5.382kJ)		*p*=0.0006, (-4.099kJ)
Hyp-3P	*p*=0.001, (-7.329kJ)	*p*=0.002, (-9.481kJ)	*p*=0.0006, (-4.099kJ)	
Numbers indicate *p*-value, (Mean difference (kJ)), after Šidák's post-hoc multiple comparisons analysis				

All models displayed strong and significant correlations with VT_2 (Linear-TW, r=0.82, r^2=0.67, p=0.007; Linear-P, r=0.77, r^2=0.59, p=0.016; Hyp-2P, r=0.84, r^2=0.71, p=0.004; Hyp-3P, r=0.84, r^2=0.71, p=0.004) and were not significantly different to VT_2 (Linear-TW, p=0.46; Linear-P, p=0.10; Hyp-2P, p=0.93; Hyp-3P, p=0.44). The lowest mean difference with VT_2 (330 ± 37W) was the Hyp-2P model (330 ± 40W), followed by Hyp-3P (324 ± 41W), Linear-TW (336 ± 39W), and Linear-P (346 ± 39W).

Chapter 6: Discussion

This study was undertaken to investigate the bioenergetics of the Critical Power model. It was hypothesised that measures associated with aerobic metabolism (W_{max}, CP, $\dot{V}O_{2max}$, VT_1, VT_2) would better predict CP while those associated with anaerobic metabolism ($\dot{V}La_{max}$, PP) would better predict W’. It also aimed to investigate the relationship between the $\dot{V}La_{max}$ and supramaximal/extreme intensity exercise, as well as compare four different CP models.

The main findings were: (a) there were no statistical differences between the power output (absolute or relative) at CP and VT_2, while absolute measures of $\dot{V}O_{2max}$ and W_{max} were strongly related to CP (W) and CP ($W·kg^{-1}$), respectively; (b) The only variables significantly related to W’ were CP ($W·kg^{-1}$) and $\dot{V}O_{2max}$ ($ml·min^{-1}·kg^{-1}$); (c) Using multiple linear regression, CP ($W·kg^{-1}$) could be significantly predicted by the relative variables of PP ($W·kg^{-1}$), $\dot{V}O_{2max}$ ($ml·min^{-1}·kg^{-1}$), $\dot{V}La_{max}$, and W’, while W’ could also be predicted by relative variables (PP ($W·kg^{-1}$), $\dot{V}O_{2max}$ ($ml·min^{-1}·kg^{-1}$), $\dot{V}La_{max}$, and W’); (d) $\dot{V}La_{max}$ and 1-min TT $W·kg^{-1}$ displayed a strong and significant relationship, while work completed above CP (kJ) in the 1-min TT was significantly less than the W’; (e) The four different Critical Power models tested produced significantly different values for CP and W’.

The participants in this study were high level road and track cyclists. Mean $\dot{V}O_{2max}$ was 70.1 ± 5.9 (60.0-79.1) $ml·min^{-1}·kg^{-1}$. The mean and upper end of this range approaches values deemed to be necessary to be a world class endurance road or track cyclist (Craig & Norton, 2001; Jeukendrup et al., 2000; Sallet et al., 2006) and is similar to the participants in the study of Bartram et al. (2017), who were elite level Australian track cyclists. The mean CP (327 ± 41, 263-393 W) and W’ (20.5 ± 5.4, 12.7-28.1 kJ) were also only slightly lower than the elite participants studied by Bartram et al. (2017) (CP: 351 ± 27; W’: 24.3 ± 4.0 kJ). PP ($W·kg^{-1}$) in the current study (17.9 ± 2.6, 14.2-22.6 $W·kg^{-1}$) was only slightly below that recorded by elite and professional road cycling sprinters under laboratory conditions (19.0 ± 1.1 $W·kg^{-1}$), and above that reported by non-sprinters (16.7 ± 1.5 $W·kg^{-1}$)(Sallet et al., 2006). This data highlights the strong aerobic and anaerobic power abilities of the riders in this study. Furthermore, one of the participants competed in endurance track cycling at the 2018 Commonwealth games, winning a gold medal, whilst another had also competed on the track in the 2018 Commonwealth games and in the 2016 Olympic road race.

6.1 Bioenergetics of the CP

The strongest relationships with power at CP were found in W_{max} (r=0.92, r^2=0.84, p=0.0005) and $\dot{V}O_{2max}$ (r=0.91, r^2=0.83, p=0.0007), however, power output associated with W_{max} and CP were significantly different (414 ± 55 vs 326 ± 41 W, p<0.0001). This supports the hypothesis that aerobic variables will be strongly associated with CP. The protocol used for determination of W_{max}, ventilatory thresholds and $\dot{V}O_{2max}$, can significantly affect the resultant power output associated with these parameters (Leo, Sabapathy, Simmonds, & Cross, 2017). However, it does not significantly alter physiological values such as the $\dot{V}O_{2max}$ or the $\dot{V}O_2$ at which the ventilatory thresholds occur (Bentley & McNaughton, 2003; Bishop, Jenkins, & Mackinnon, 1998; Julio, Panissa, Shiroma, & Franchini, 2017; Roffey, Byrne, & Hills, 2007). The current study found a strong correlation (r=0.85, r^2=0.73, p=0.003) between power output at CP and VT_2, while post-hoc analysis revealed no significant difference in power outputs between the two (p=0.91). This indicates the CP model (Lin-TW) and protocols used in the current study may be a valid way to determine power output at VT_2. However, the literature infers a comparison of the $\dot{V}O_2$ at VT_2 and the $\dot{V}O_2$ at CP may be a more useful measure to authenticate the relationship between these parameters, as the associated mechanical power output varies based on test protocol (Bentley & McNaughton, 2003; Julio et al., 2017).

Previous research has confirmed the relationship between $\dot{V}O_2$ at both CP and VT_2. Keir et al. (2015) found no significant difference (p>0.05) in the $\dot{V}O_2$ values at CP and VT_2 (3.29 ± 0.48 vs. 3.34 ± 0.45 $L \cdot min^{-1}$) despite finding significant differences (p<0.05) between power output at CP and VT_2 (226 ± 45 vs. 262 ± 48 W). The study used a very similar ramp test to the current study (25 vs. 30 $W \cdot min^{-1}$) for determining VT_2, but used more time trials to exhaustion (4-5), ranging between 1-20min to determine CP. These tests are substantially longer than the efforts used in the current study, which could explain the conflicting findings. Similarly, Dekerle et al. (2003) also used a 25 $W \cdot min^{-1}$ ramp test to determine the power and $\dot{V}O_2$ associated with VT_2 along with time to exhaustion trials to determine CP. The trials to exhaustion matched the duration of trials used in the current compared to those used by Keir et al. (2015) and concurred that power output at CP and VT_2 (278 ± 22 vs 286 ± 28 W) are not significantly different (p=0.96). These findings along with the strong relationships between variables indicative of aerobic performance (Table 4), support the findings of previous research where CP is suggested to be highly aerobic in nature and related to a steady state performance intensity (Dekerle et al., 2012; Heubert et al., 2005; Jones et al., 2010; Vanhatalo & Jones, 2009).

Multiple regression including relative physiological variables representative of the maximal capacity of the glycolytic ($\dot{V}La_{max}$), aerobic ($\dot{V}O_{2max}$ ml·min^{-1}·kg^{-1}) and ATP-PCr (PP W·kg^{-1}) systems, as well as work capacity above the steady state (W'), was able to significantly predict CP (W·kg^{-1}). Importantly, the predictive equation showed a greater $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}) resulted in a greater CP (W·kg^{-1}), while a greater $\dot{V}La_{max}$ resulted in a lower CP (W·kg^{-1}). This supports the model used by Adam et al. (2015) and Hauser et al. (2014), where $\dot{V}O_{2max}$ is positively related and $\dot{V}La_{max}$ is negatively related to the maximal lactate steady state. While previous research has shown maximal lactate steady state and CP occur at significantly different power outputs (Dekerle et al., 2003; Pringle & Jones, 2002), they are both used as markers of a steady-state intensity and found to be strongly correlated (r=0.95, p<0.01) in previous research (Pringle & Jones, 2002). These findings along with the current study's findings support the earlier work of Mader and Heck (1986), who stated in their theory of the "anaerobic threshold" that a metabolic steady state occurs at the intensity where the production of lactate by the glycolytic system is matched by the combustion of lactate by the aerobic system. This theory and model are now utilised by online training applications (INSCYD, Salenstein, Switzerland) and professional cycling teams to monitor and inform training programmes, however, despite the increasing use of this model in the industry setting there have been few studies conducted to confirm its validity. The results of the current study provide some support for this model through the positive influence of $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}) on CP (W·kg^{-1}) and negative influence of $\dot{V}La_{max}$ on CP (W·kg^{-1}) in the regression equation (Figure 10A, Table 5), however, more research is needed in this area to interpret these findings with confidence.

6.2 Bioenergetics of the W'

It was hypothesised that variables associated with anaerobic metabolism would be strongly related to the W', however, the only variables to display a significant relationship with the W' were $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}) (r=-0.67, r^2=0.45, p=0.047) and CP (W·kg^{-1}) (r=0.89, r^2=0.79, p=0.0014). As neither of these variables were directly related to anaerobic metabolism the hypothesis that the W’ will be strongly related to anaerobic variables cannot be accepted. This may indicate the W’ better represents a utilisation of multiple energy systems in unison to sustain severe intensity exercise than it does an anaerobic capability.

Interestingly, the correlations between W’ and both $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}) and CP (W·kg^{-1}) were both negative. It is not logical to assume a lower CP (W·kg^{-1}) or $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}), which are both strongly associated with aerobic capabilities, would be related to a greater ability to perform work in excess of CP. However, the W’ has been related to anaerobic capabilities in previous work (Hill & Smith, 1993; Nebelsick-Gullett et al., 1988; Vandewalle et al., 1997), while anaerobic capabilities in cycling have been positively related to lean body mass (Galán-Rioja, González-Mohíno, Sanders, Mellado, & González-Ravé, 2020; Perez-Gomez et al., 2008). It is therefore plausible that a greater lean body mass is related to a greater W’. However, this would likely increase body mass, decreasing the relative measures of $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}) and CP (W·kg^{-1}), which is supported by the tendency for body mass to be almost significantly related (r=0.57, r^2=0.33, p=0.11) to the W’ in the current study. The relationship between CP, W’, and total lean body mass and lean body mass specifically in the thigh musculature has been the topic of recent investigation by Byrd, Wallace, Clasey, and Bergstrom (2021), with their results supporting the theory that W’ is related to lean body mass. It was found that lean thigh mass was able to significantly predict W’ (W’ = ((0.8*Thigh lean mass) + 3.7), r^2=0.48, p=0.004), while total lean body mass significantly predicted CP (W) (CP(W) = ((2.3*Lean body mass) + 56.7), r^2=0.35, p=0.021), but was not significantly correlated with CP (W·kg^{-1}) (r=0.14, r^2=0.02, p=0.62). This indicates that in cyclists greater muscle mass, especially in the lower limb, is associated with greater W’, but lower relative aerobic performance measures, supporting the results of the current study.

Multiple regression using relative variables (PP (W·kg^{-1}), $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}), $\dot{V}La_{max}$, and CP (W·kg^{-1}), Figure 10-C, Table 7) enabled significant predictions of W’, while absolute variables (PP (W), $\dot{V}O_{2max}$ (L·min^{-1}), $\dot{V}La_{max}$, and CP (W), Figure 10-D, Table 8) did not. Both relative predictive equations for CP (p=0.001, r^2=0.978, adjusted r^2=0.956) and W’ (p=0.034, r^2=0.890, adjusted r^2=0.779) were strong and significant. However, it is clear to see the prediction of relative CP (SEE=0.11 W·kg^{-1}, Figure 10-A, Table 5) is clustered much closer to the regression line with fewer data points outside the 95% confidence limits than the prediction of W' (SEE=2.51kJ, Figure 10-C, Table 7). This illustrates the difficulty of studying the W'. While the CP appears strongly related to $\dot{V}O_{2max}$ and not significantly different to VT_2, there is no similar physiological measure the W' can be related to. Furthermore, the W' appears to be influenced by a wide range of factors including the buffering capacity and tolerance to metabolites (Chidnok, Fulford, et al., 2013; Johnson, Mills, Brown, & Sharpe, 2014; Vanhatalo, Fulford, DiMenna, & Jones, 2010), and the ATP-PCr system as evidenced through phosphocreatine supplementation studies (Eckerson et al., 2005; Miura et al., 1999).

The hypothesis predicted that the glycolytic system, measured by $\dot{V}La_{max}$, would be strongly related to the W' due to the proposed anaerobic nature of the W' in previous research (Hill & Smith, 1993; Vandewalle et al., 1997). W' and $\dot{V}La_{max}$ displayed a moderately strong relationship (r=0.66, r^2=0.44) which would have led to the conclusion that the glycolytic capacity is a large contributor to the W', however, this did not reach statistical significance *(p*=0.051). Performing large quantities of work in the severe intensity exercise domain is a requirement for success in many road and track cycling events (Ebert et al., 2006; Jeukendrup et al., 2000; Van Erp & Sanders, 2020), therefore, understanding the bioenergetics and determinants of the W' is important to optimise training programme to develop the ability to perform severe intensity exercise. Given the proximity with which the *p*-value was to statistical significance, this is an area which should be investigated further.

6.3 Supramaximal 1-minute TT

This study aimed to investigate the relationship between the $\dot{V}La_{max}$ and supramaximal/extreme intensity exercise. The 1-min TT was completed at 176 ± 21 (148-204) % of CP with all participants displaying a gradual decline in power (Figure 11), indicating a positive pacing strategy and no under pacing of the test. Previous research has indicated that untrained participants can reach $\dot{V}O_{2max}$ in the first 60-s of an all-out exercise bout (Jones et al., 2010). This is not always the case with more well trained participants, where $\dot{V}O_{2max}$ has not been reached at the end of a 90-s 'all-out' exercise bout (Brickley, Dekerle, Hammond, Pringle, & Carter, 2007). This is despite the 'all-out' pacing strategy, where participants exert maximal effort from the beginning of the effort, being shown to increase the speed of both the phase II and overall $\dot{V}O_2$ kinetics compared to more conservative pacing strategies (Aisbett, Lerossignol, McConell, Abbiss, & Snow, 2009; Bailey, Vanhatalo, Black, DiMenna, & Jones, 2016; Bailey et al., 2011). The influence of training status is likely due to the tendency for endurance training to increase the speed of the phase II kinetics (Berger & Jones, 2007; Koppo, Bouckaert, & Jones, 2004), but reduce the rate of increase of the slow component (Carter et al., 2000; Gaesser, 1994; Lucía, Hoyos, & Chicharro, 2000). Given the highly trained nature of the participants in the current study and the requested 'best paced' effort, which was positively paced, but not 'all-out' from the start, it is unlikely participants spent substantial time at $\dot{V}O_{2max}$ during the 1-min TT. This can therefore be classified as an extreme intensity domain effort (Hill et al., 2002).

It has been suggested that 40% of the energy demand of a maximal 1-min effort is derived through glycolysis (Craig & Norton, 2001; Jeukendrup et al., 2000). This was evident in the strong and significant relationship between relative ($W \cdot kg^{-1}$) 1-min TT power and $\dot{V}La_{max}$ (r=0.85, r^2=0.73, p=0.0016). Thus, indicating that the power output during extreme intensity exercise is highly reliant on the glycolytic capacity ($\dot{V}La_{max}$). Cyclists wanting to improve their performance in extreme intensity domain efforts may wish to focus on increasing their $\dot{V}La_{max}$, however, the influence of $\dot{V}La_{max}$ on performance in this domain needs to be investigated further before the evidence could be considered conclusive.

In the CP model the W' is a set amount of work that can be completed above CP before exercise intensity must decrease to CP or below (Jones et al., 2010), with the model assuming the 'non-fatigable' power associated with the CP and the aerobic system is available immediately at the start of exercise (Jones et al., 2010; Morton, 2006). In reality there is a delay between the imposition of a work-rate and the increase in O_2 utilisation. It can take approximately 5-15-s for the $\dot{V}O_2$ to respond to the work-rate and 15-40-s to progress through the phase II kinetics, after which the $\dot{V}O_2$ continues to progress towards maximum through the slow component phase (Berger & Jones, 2007; Koppo et al., 2004). This may be a reason the work completed above CP in the 1-min TT was significantly less than the W' (14.7 ± 3.8 vs 20.5 ± 5.3 kJ, p=0.0008) in the current study. Efforts of this intensity and duration display high anaerobic and aerobic energy demands, however, the aerobic contribution is significantly less than during longer efforts (Jeukendrup et al., 2000), and takes time to respond to the work-rate (Berger & Jones, 2007; Koppo et al., 2004).

Therefore, the full aerobic capacity of the CP is not immediately available at the start of the effort, meaning the work completed above CP is significantly underpredicted by the CP model. These finding support the suggestions that efforts shorter than 3.5-min display a non-linear time-work relationship (Vandewalle et al., 1997), and that CP models overestimate the power that can be sustained for short exercise durations due to the $\dot{V}O_2$ kinetics (Vinetti et al., 2019). The CP model assumptions that the full aerobic potential of the CP is available immediately at the start of exercise and that the anaerobic component of energy supply is not rate limited (Jones et al., 2010; Morton, 2006), are overly simplistic. Energy systems work in unison and are reliant on each other for continued activation (Gastin, 2001). Therefore, the utilisation of a model which holds physiological parameters constant throughout the entire intensity and duration spectrum does not align with the actual bioenergetics of the work taking place.

6.4 Differences Between Critical Power Models

A secondary aim was to compare different CP models to determine the influence the modelling method has on the CP and W' parameters and if any models align with physiological parameters of performance, such as VT_2, better than others. The Linear-TW, Linear-P, Hyp-2P, and Hyp-3P models were used to calculate CP and W' according to the formulas in table 1.

Significant differences (p<0.001) were found between CP and W' from the different models, with post-hoc analysis revealing these differences were significant between every model (Table 9 and 10). Those models providing the highest CP values predicted the lowest W' values and vice versa (Figure 13). This aligns with the results of previous research (Bergstrom et al., 2014; Bull et al., 2000; Gaesser et al., 1995). The mean difference between the lowest and highest CP estimates (Hyp-3P and Linear-P models, respectively) was only 22 ± 11W, however, this ranged from 5-39W at the individual participant level. The mean difference in W' was 9.48 ± 4.48 kJ, between the Hyp-3P and Linear-P models with a range of 2.73-15.91 kJ. Furthermore, the variation in CP and W' between the four models was large, particularly when considered at the individual level. As a group mean the CV for CP was 2.9%, but ranged from 0.63-6.11% at the individual level, while W' displayed larger variation with a group mean of 22.8%, and range of 9.56-33.75% between models. A CV of

2.9% may be deemed acceptable variation for measurement of CP by coaches as both the relaibility and repeatability of power metres and biological variation need to be considered (Hopkins, 2000). However, variation in CP of 6.11% or up to 39W between models would likely result in vastly different training intensities and programming than if another CP model had been used. With regards to W’ the CV (22.8%) is not at an acceptable level of variation between models at the group mean or at the individual level. Unlike CP which can be validated against VT_2 as a criterion measure, there is no such substitute for W’, making it difficult to provide a recommendation on the most valid model. This variation makes it difficult to use different models interchangably, or to have confidence in the CP and W’ values calculated from software apllications where the modelling method is not explicitily stated.

With regards to VT_2, the CP of all models in the current study was not significantly different to VT_2. The Hyp-2P model showed the lowest mean difference to VT_2 (0W), followed by Hyp-3P (6W), Linear-TW (6W), and Linear-P (16W). Gaesser et al. (1995) stated that the Hyp-3P model produces the closest CP estimates to VT_2. This conflicts with the results of the current study where the Hyp-2P model showed the lowest mean difference between CP and VT_2, however, the Hyp-3P model in the current study did produce CP estimates with a mean difference of only 6W (1.8%) from VT_2 which is small considering small differences greater than this can also occur in the method used to determine VT_2 (Gaskill et al., 2001).

It may be best for practitioners to ustilise a single model consisitently and use efforts related to the nature of the events the cyclist is competing in to populate data for the model. For example, Bartram et al. (2017), suggest using one, four, and 10 minute efforts to calculate CP and W’ for endurance track cyclists. Including short duration efforts in the CP model leads to higher estimates of CP (Bishop, Gjenkins, & Howard, 1998; Vandewalle et al., 1997), however, this matches the short nature of many track cycling events (Craig & Norton, 2001). Therefore, a higher CP simply matches the demands of the event more closely and relate to a more critical training work rate. Similarly, CP modelling involving longer durations tests could be applied to road cycling, which may better reflect the longer duration of road cycling competitions (Van Erp & Sanders, 2020). As such, the CP becomes a work rate or performance related parameter rather than a paramter of physiological performance. While

CP and VT_2 were not significantly different between models, the large variability in CP within models from single participants (CV range=0.63-6.11%) makes it difficult to recommend any model which best aligns CP with VT_2. Likewise, as W' (CV range=9.56-33.75%) has no criterion measure to validate the model against, a best model for calculating this parameter cannot be determined. Therefore, consistent utilisation of a single CP model and similar effort durations can be used as a tool to monitor the power performance capability of cyclists. However, physiological indices of performance should not be assumed from CP modelling, but rather should be obtained from physiological data using the same testing protocol each time.

6.5 $\dot{V}La_{max}$ and Supramaximal Exercise

An interesting finding of this research was the strong relationship between power output (W and $W \cdot kg^{-1}$) in the $\dot{V}La_{max}$ test (Test end power, Mean test power, power over the lactic interval) and the $\dot{V}La_{max}$ ($mmol \cdot L^{-1} \cdot s^{-1}$). Previous research has considered the effect of the $\dot{V}La_{max}$ on the maximal lactate steady state but has not attempted to predict $\dot{V}La_{max}$ from power output alone (Adam et al., 2015; Nitzsche, Baumgärtel, & Schulz, 2018).

It was thought $\dot{V}La_{max}$ test end power, defined as the last two seconds of the $\dot{V}La_{max}$ test, would best represent the 'glycolytic' power output, owing to the fact the contribution from the ATP-PCr system would be largely depleted (Gastin, 2001; Wells et al., 2009) and the aerobic system would not yet be activated to a significant level after this duration (Bailey et al., 2009; Burnley & Jones, 2007). The strongest and most significant relationship, however, was between power over the lactic interval of the test (Time period between PP minus 3.5% and the end of the test) and $\dot{V}La_{max}$ for both absolute (r=0.80, r^2=0.65, p=0.005) and relative (r=0.87, r^2=0.75, p=0.0011) power outputs.

Adam et al. (2015), tested the reliability of the $\dot{V}La_{max}$ test, over the course of three $\dot{V}La_{max}$ tests over a period of less than three weeks, they found intraclass coefficient correlations of 0.904, CV of 6.3%, and a reliable change index of 0.11 $mmol \cdot L \cdot s^{-1}$. This led to the conclusion that changes in $\dot{V}La_{max}$ greater than 0.11 $mmol \cdot L \cdot s^{-1}$ could be deemed reliable and due to a training effect rather than variation in testing. More research into the reliability of this parameter is needed to confirm this reliable change index given the size of the CV. In the current study a regression equation using power over the lactic interval

(Figure 8-A, Table 2) only managed to predict $\dot{V}La_{max}$ within this range for three participants. However, when the lactic interval power as W·kg^{-1} was used the equation (Figure 8-B, Table 3) $\dot{V}La_{max}$ was predicted within this range for all but one participant. This supports the theory $\dot{V}La_{max}$ could be predicted from power output in a 15-s isokinetic sprint test without the need for lactate measurements. Predictions of this nature have recently been added to performance monitoring and training software (TrainingPeaks WKO5, Boulder, CO, USA; and INSCYD), where the $\dot{V}La_{max}$ is being estimated using power and anthropometric data alone. The accuracy of these estimations has not been validated. However, given the increasing use of $\dot{V}La_{max}$ in software applications by coaches to inform training programmes the validation $\dot{V}La_{max}$ estimated from power data is an important topic for future research. The influence of $\dot{V}La_{max}$ on performance is another area requiring research. Athletes wishing to improve their W' may focus on improving their anaerobic performance capabilities, including $\dot{V}La_{max}$. However, the current study suggests $\dot{V}La_{max}$ is at best only one of several components which comprise the W'.

6.6 Limitations

Due to unforeseen issues with disc brake compatibility and availability of disc brake compatible trainers three different smart trainers were used for the TT efforts. No noteworthy power differences were found between the three smart trainers used in the study and all participants used the same trainer, providing consistency of measurement for each participants data. It is possible the inertia and resistance provided by the different trainers may result in a different ride feel which could have a small impact on performance (Hansen, Jørgensen, Jensen, Fregly, & Sjøgaard, 2002), although this is likely negligible. The differences introduced by this are likely to be minor but performing all testing on a single trainer or ergometer would be the gold standard.

The various power measures from the $\dot{V}La_{max}$ test, linear regression prediction of $\dot{V}La_{max}$, and the multiple regression predictions of CP and W' which used $\dot{V}La_{max}$ were all stronger and of greater significance when relative measures were used. This may be in part due to the $\dot{V}La_{max}$ being influenced by lactate distribution space, meaning it could be considered a relative rather than absolute measure of glycolytic capacity. Blood lactate is measured as mmol·L^{-1}, however, this is a measurement of lactate concentration, not an absolute quantity. Lactate is water soluble and diffuses across water space in the body, therefore, a larger individual has more litres of lactate distribution space and a greater absolute lactate production for the same lactate concentration in mmol·L^{-1} (Mader & Heck, 1986). According to Mader and Heck (1986), lactate is distributed across the 'active' and 'passive' distribution space in the body, which is mainly the muscle and the blood respectively. It cannot be assumed that there is rapid diffusion and therefore equal lactate concentration across both compartments in non-steady state conditions, however, it is noted the lactate concentration measured in the blood is proportional to that of the total lactate concentration in the entire lactate distribution space regardless of an established equilibrium. Previous research has suggested lactate distribution space comprises 40-44% of the total body mass (Hauser et al., 2014; Mader & Heck, 1986). This distribution space depends on factors such as the amount of fat mass and hydration status. However, adjusting the lactate concentration to be equivalent for body mass may influence the results of this study when comparing $\dot{V}La_{max}$ with other variables, however, doing so would rely on an accurate measurement of the lactate distribution space and knowledge of the speed and equilibrium of the lactate kinetics from the muscle to the blood. At the current time it is not possible to accurately or reliably estimate whole body lactate production based on body mass, therefore, using the $\dot{V}La_{max}$ in mmol·L^{-1}·s^{-1} is likely the best option currently available to monitor glycolytic capacity.

6.7 Future Research

This research has provided further information regarding the energetic composition of the CP model. Research regarding non energetic factors such as how the ability to tolerate metabolites influences the W' is currently lacking. It has been shown that several muscle metabolites reach critical levels at exhaustion (Chidnok, DiMenna, et al., 2013), but the influence of these critical levels on the magnitude of the W' is unknown.

It is also unknown if similar results to this study would be observed in female participants. The menstrual cycle and hormone fluctuations are known to influence female performance and exercise metabolism (Oosthuyse & Bosch, 2010). The effects on CP, W' and $\dot{V}La_{max}$ would be a topic relevant to female cyclists and their coaches alike.

A key component of the research was investing the relationship between the $\dot{V}La_{max}$ and the W'. The relationship found was reasonably strong, however, the findings narrowly failed to reach statistical significance. Further research into this relationship should be undertaken to expand on these findings and provide greater clarity about this relationship.

It was found in this study among others that the different CP models produce different CP and W' estimates. Future research should aim to determine if there is a CP model and testing protocol which can accurately match the maximal metabolic steady-state with CP and the work capacity above this steady state with W'. If such a protocol could be developed it would drastically reduce the reliance on laboratory testing to determine these parameters which would be of practical use to many athletes and coaches.

The finding that $\dot{V}La_{max}$ and power over the lactic interval were correlated extremely strongly and with relatively low error shows the need for further research into predicting the $\dot{V}La_{max}$ through power measurement alone. Several training software providers are already providing an estimate of $\dot{V}La_{max}$ from power data, however, there is no validation of these measures or explanation of the methods used to calculate them. Research into the ability to determine the $\dot{V}La_{max}$ with on road power testing would also be useful to determine if the $\dot{V}La_{max}$ can be measured without the need for specialist equipment, while the usefulness of the $\dot{V}La_{max}$ as a paramter to inform training programmes also requires further study.

Research into the types of training and interventions which affect the $\dot{V}La_{max}$ would also be of use to cyclists and coaches. Many coaches are beginning to work with this parameter in their testing and training of cyclists, however, hard evidence into how to influence this parameter does not currently exist. Currently anecdotes from coaches the only current information regarding $\dot{V}La_{max}$ and training. Research investigating the importance of the W' on various types of cycling competitions would also be useful. The CP has previously been considered the critical performance measure for endurance performance, however, when cyclists with similar CP compete it may be the magnitude of the W' or recovery of W' during intermittent efforts which decides the winner.

Chapter 7: Conclusion

The purpose of the study was to enhance the understanding of the bioenergetics underpinning the CP model, the relationship between $\dot{V}La_{max}$ and extreme intensity exercise, and to compare the CP and W' values derived from four different CP models.

The main findings of the study were that indices of performance associated with aerobic capacity (W_{max}, $\dot{V}O_{2max}$, VT_1 and VT_2 power outputs) were strongly related to the CP, with power output at CP and VT_2 not being significantly different. No significant relationships were found between measures associated with anaerobic capacity (Peak power, $\dot{V}La_{max}$) and W'. Significant negative relationships between $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1}) and CP (W·kg^{-1}) were found and hypothesised to be due to differences in lean body mass. Thus, the CP can be related to aerobic performance, whilst more work is required to enhance the understanding of the bioenergetics of the W'.

The relative power output (W·kg^{-1}) in the 1-min TT and $\dot{V}La_{max}$ were clearly related, indicating a strong association between the glycolytic capacity and extreme intensity exercise performance. Despite this relationship, the $\dot{V}La_{max}$ was not significantly related to the W', however, this did approach statistical significance indicating it is an area requiring further research. Although the 1-min TT was performed in the extreme intensity domain, the power output was insufficient to deplete W'. It was proposed this occurred because of the delay associated with the $\dot{V}O_2$ kinetics, however, this was not measured in the current study. All CP models tested produced significantly different CP and W' values, with W' being the most affected by the utilisation of different models. This led to the conclusion the theory behind the CP model is overly simplistic with regards to energy system utilisation and should be used as a tool to monitor power performance capability, but not as a method of estimating physiological performance measures. Finally, it was found that the $\dot{V}La_{max}$ and power over the lactic interval of the $\dot{V}La_{max}$ test were extremely strongly correlated. This may be of practical use for coaches who wish to measure the $\dot{V}La_{max}$ of cyclists in a time and cost-effective manner, but further study is required to strengthen these findings.

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Appendixes

Appendix 1: Information sheet

MASSEY UNIVERSITY
COLLEGE OF HEALTH
TE KURA HAUORA TANGATA

Investigating the bioenergetic and mathematical determinants of the Critical Power model in elite cyclists.

INFORMATION SHEET

Researcher Introduction

Boris Clark is conducting this research project with the help of his supervisor Dr. Paul Macdermid. It helps form the thesis component of his Master of Health Science, Sport and Exercise Degree. The research is aiming to determine the relationship between VLamax and W' in elite male cyclists.

Project Description and Invitation

When cycling at intensities above critical power there is an energetic reserve capacity known as W' (pronounced W-Prime). The W' displays a linear work-time relationship meaning there is a predictable relationship between the power output of a cyclist and the duration they will be able to ride at this intensity before fatigue occurs.
The linear work-time relationship appears to hold true until the effort duration is short enough that the VO2 kinetics do not have time to reach a steady-state before fatigue occurs. This intensity is known as the extreme exercise domain.
It is the aim of this research to determine the relationship between the VLamax and the size of the W' as well as the VLamax and the ability to perform work in the extreme exercise domain.

You are invited to participate in this research project if you meet the criteria set out below:

Participant Identification and Recruitment

- *Participants will be recruited through word of mouth, email, and the researchers contact with the coaches of local elite male cycling teams.*
- *Participants must be aged 17-40 years old at the time of the study, male, and be considered an 'elite level' cyclist on the track or road. To be considered 'elite level', cyclists should be competing in at least 'A' grade in their local racing and should be competitive in national and international level competitions.*
- *Participants will be required to complete a medical screening questionnaire prior to taking part in the study. If there is an injury or underlying health condition that may put the participant at risk if they will not be allowed to take part.*
- *Those who do not meet the above criteria are excluded from participation in the study. Please contact the lead researcher Boris Clark if you are unsure if you meet these criteria.*
- *The study aims to recruit a minimum of 10 participants. This is a similar number to previous studies on elite cyclists (Bartram et al., 2017).*
- *In return for their time and contribution to the study participants will receive information pertaining to their cycling performance, such as their VO2max, VLamax, Critical power, W', and an explanation around what these results mean for their performance.*

- *Participants will be made aware intense exercise carries some risk, as does the puncture of the skin to take a lactate sample. The puncture of the skin may also cause mild discomfort. The researchers will take precautions to avoid any injury or unnecessary discomfort to study participants.*

Project Procedure

- *Participants will have their height and weight measured prior to testing.*
- *The VLamax test involves taking lactate measurements from the ear lobe. This requires a small puncture to the skin to obtain a drop of blood and is normally not painful. The participant will then sprint on a cycle ergometer for 15 seconds with lactate measurements being taken before and after the sprint.*
- *The VO2max test will be a graded exercise tests where the participant cycles on an ergometer with progressively harder resistance until exhaustion.*
- *Participants will complete 3 maximum effort time trials of 1, 4, and 10-minutes duration.*
- *The maximum effort time trials will be conducted on the participants own bikes with their own power meters on a stationary trainer.*
- *Testing will require the participant to be available on 3 days for 5 tests to be completed over a period of less than 3 weeks. The tests are listed below:*
- *The VLamax test, which will take approximately 35-minutes including the warm-up and preparation for the test.*
- *The VO2max test which will be conducted on the same day as the VLamax test and takes an additional 30-minutes including preparation for the test.*
- *The time trials of 1, 4, and 10-minutes.*
- *The VLamax test, VO2max test, and 1-minute maximum effort time trial will take place in the same session. The 4 and 10-minute tests will be completed in separate sessions.*
- *It is anticipated the total time commitment will be no more than 4 hours total spread over 3 separate sessions.*

Data Management

- *Data from participants will be collected to perform the calculations and statistical analysis necessary for the research.*
- *Data obtained from the participants tests will be inputted into an excel spreadsheet on the lead researchers laptop.*
- *The data will be stored on the lead researchers laptop which is password protected.*
- *The final research will be published on the Massey University website and a summary of the findings will be available on request from the lead researcher.*
- *No participants personal information will be used in any publication or publicly available document. Participant details will only be known by the research team.*

Participant's Rights

You are under no obligation to accept this invitation. If you decide to participate, you have the right to:

- *Decline to answer any particular question;*
- *Withdraw from the study at any time;*
- *Ask any questions about the study at any time;*
- *Provide information on the understanding that your name will not be used unless you give permission to the researcher;*
- *Be given access to a summary of the project findings when it is concluded.*

Project Contacts

- *Lead Researcher (Boris Clark)*
  - *Phone: 0221877570*
  - *Email:* borisclark52@ymail.com
- *Supervisor (Dr. Paul Macdermid)*
  - *Phone: (06) 9516824 ext: 83824*
  - *Email: p.w.macdermid@massey.ac.nz*
- *You are welcome to contact either of the researchers if you have any questions or queries about participation in the research.*

Committee Approval Statement

This project has been reviewed and approved by the Massey University Human Ethics Committee: Southern A, Application 20/42. If you have any concerns about the conduct of this research, please contact Dr Negar Partow, Chair, Massey University Human Ethics Committee: Southern A, telephone 04 801 5799 x 63363, email humanethicsoutha@massey.ac.nz.

Compensation for Injury

If physical injury results from your participation in this study, you should visit a treatment provider to make a claim to ACC as soon as possible. ACC cover and entitlements are not automatic and your claim will be assessed by ACC in accordance with the Accident Compensation Act 2001. If your claim is accepted, ACC must inform you of your entitlements, and must help you access those entitlements. Entitlements may include, but not be limited to, treatment costs, travel costs for rehabilitation, loss of earnings, and/or lump sum for permanent impairment. Compensation for mental trauma may also be included, but only if this is incurred as a result of physical injury.

If your ACC claim is not accepted you should immediately contact the researcher. The researcher will initiate processes to ensure you receive compensation equivalent to that to which you would have been entitled had ACC accepted your claim.

Appendix 2: Pre-exercise Screening Form

Investigating the bioenergetic and mathematical determinants of the Critical Power model in elite cyclists.	***School of Sport and Exercise, College of Health*** *Private Bag 11 222* *Palmerston North,* *New Zealand* *Telephone: 64 6 356 9099 ext. 7763*

Pre-Exercise Questionnaire and Informed Consent

Please take few minutes to answer the following questions.

Name:____________________________________ Age:________ Sex:________

Address: ____

1. Have you ever had any injury, illness, back or joint injury, muscular pain that may be aggravated by vigorous exercise? Yes/No
2. Have you ever had: Arthritis, Asthma, Diabetes, Epilepsy, Hernia, Ulcer or Dizziness? Yes/No
3. Have you ever had a Heart Condition, High Blood Pressure, Stroke, High Cholesterol, Pain in the chest? Yes/No
4. Have any immediate family had heart problems prior to age 60? Yes/No
5. Are you now or have you recently been pregnant? Yes/No
6. Are you taking any prescribed medication? Yes/No
7. Have you been hospitalised recently? Yes/No
8. Is there any reason not mentioned above that may prevent or affect your ability to perform this test? Yes/No

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IF YOU ANSWERED YES, PLEASE PROVIDE MORE INFORMATION (TYPE, COMMENT)

____

____

1. **I have read the information sheet on the appropriate test protocol and have had the details of the test explained to me in full. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.**
2. **I understand that I have the right to withdraw my consent at any time and to decline to answer any particular questions.**

3. **I understand that a maximal test may be potentially hazardous to persons with cardiovascular anomalies (heart problems).**
4. **I have completed a pre-exercise safety questionnaire and have been approved as being suitably fit and healthy to take part in the fitness test.**
5. **I have read this form and I agree to participate in this test under the conditions set out in the information sheet.**

Signed: Date: / /

Witness: Date: / /

This project has been reviewed and approved by the Massey University Human Ethics Committee, Southern A, Application 20/42

Appendix 3: Informed Consent Form

MASSEY UNIVERSITY
COLLEGE OF HEALTH
TE KURA HAUORA TANGATA

School of Sport and Exercise,
College of Health
Private Bag 11 222
Palmerston North,
New Zealand
Telephone: 64 6 356 9099 ext. 7763

Investigating the bioenergetic and mathematical determinants of the Critical Power model in elite cyclists.

PARTICIPANT CONSENT FORM

I have read, or have had read to me in my first language, and I understand the Information Sheet attached as Appendix I. I have had the details of the study explained to me, any questions I had have been answered to my satisfaction, and I understand that I may ask further questions at any time. I have been given sufficient time to consider whether to participate in this study and I understand participation is voluntary and that I may withdraw from the study at any time.

1. I agree to participate in this study under the conditions set out in the Information Sheet.

Declaration by Participant:

I ______________________ hereby consent to take part in this study.

Signature: ________________________ Date: _________________

Appendix 4: Power Data Comparison

To check for differences in power readings between smart trainers each trainer was compared to a single InfoCrank power meter. The InfoCrank has been found to be accurate and reliable (Maier et al., 2017). Any inconsistencies in between power data logged from the smart trainers compared to the InfoCrank would be indicative of a difference in power measurement between the smart trainers.

A ramp test of 30W·min^{-1} was performed on each smart trainer used in the study compared to the InfoCrank power meter. The power data averaged over a range of time periods and power outputs, along with the coefficient of variation is presented for each trainer in table 11.

Table 11: Comparison of smart trainers to Infocrank Power meter over a range of intensities and durations

Time	10s			30s			1-min		
	Power (W)		CV (%)	Power (W)		CV (%)	Power (W)		CV (%)
	NEO	IC		NEO	IC		NEO	IC	
	280	285	1.25	274	275	0.26	268	268	0.00
	333	331	0.43	330	326	0.86	323	319	0.88
	390	383	1.28	386	381	0.92	379	377	0.37
	450	444	0.95	447	444	0.48	438	434	0.65
Mean	**363**	**361**	**0.98**	**359**	**357**	**0.63**	**352**	**350**	**0.48**
	KICKR	IC		KICKR	IC		KICKR	IC	
	281	282	0.25	279	280	0.25	270	274	1.04
	338	339	0.21	337	334	0.63	327	328	0.22
	397	385	2.17	386	383	0.55	378	376	0.38
	452	452	0.00	444	447	0.48	437	436	0.16
Mean	**367**	**365**	**0.66**	**362**	**361**	**0.48**	**353**	**354**	**0.45**
	SUITO	IC		SUITO	IC		SUITO	IC	
	287	280	1.75	287	282	1.24	280	272	2.05
	356	368	2.34	340	350	2.05	330	334	0.85
	382	393	2.01	380	390	1.84	375	385	1.86
	453	464	1.70	437	447	1.60	433	442	1.45
Mean	**370**	**376**	**1.95**	**361**	**367**	**1.68**	**355**	**358**	**1.55**

Time	2-min			5-min			10-min		
	Power (W)		CV (%)	Power (W)		CV (%)	Power (W)		CV (%)
	NEO	IC		NEO	IC		NEO	IC	
	252	255	0.84	263	262	0.27	305	303	0.47
	310	305	1.15	380	376	0.75			
	366	363	0.58						
	423	419	0.67						
Mean	**338**	**336**	**0.81**	**322**	**319**	**0.51**	**305**	**303**	**0.47**
	KICKR	IC		KICKR	IC		KICKR	IC	
	256	259	0.82	261	264	0.81	303	305	0.47
	312	313	0.23	378	377	0.19			
	363	362	0.20						
	424	422	0.33						
Mean	**339**	**339**	**0.39**	**320**	**321**	**0.50**	**303**	**305**	**0.47**
	SUITO	IC		SUITO	IC		SUITO	IC	
	266	255	2.99	262	252	2.75	300	296	0.95
	312	310	0.45	373	381	1.50			
	361	369	1.55						
	418	426	1.34						
Mean	**339**	**340**	**1.58**	**318**	**317**	**2.13**	**300**	**296**	**0.95**
Smart Trainer	**NEO**			**KICKR**			**SUITO**		
Mean CV (%)	**0.64**			**0.49**			**1.64**		

SUITO = Elite Suito; KICKR = Wahoo KICKR; NEO = TACX Neo; IC= InfoCrank

All smart trainers showed low coefficients of variation compared to the InfoCrank. The Elite Suito showed the greatest variation, however, the mean variation was well within an acceptable coefficient of variation (Hopkins et al., 2009).

Appendix 5: D’Agostino and Pearson’s normality test data

Table 12: D'Agostino and Pearson's normality test data

	CP (W)	**W’ (kJ)**	**$\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1})**	**$\dot{V}O_{2max}$ (L·min^{-1})**	**$\dot{V}La_{max}$ (mmol·L·s^{-1})**	**W_{max}**	**$\dot{V}La_{max}$**	**1-min TT (W)**	**4-min TT (W)**	**10-min TT (W)**
K2	0.05277	0.4305	0.9665	0.3412	1.013	1.868	14.82	5.047	1.377	0.4986
***p*-value**	0.9740	0.8063	0.6168	0.8432	0.6026	0.3930	0.0006	0.0802	0.5023	0.7794