Calculating Critical Power and the Finite Work Capacity

from a Single All-out Cycling Test

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ABSTRACT

Critical power (CP) is an important training threshold and represents the highest power output that elicits steady-state physiological responses. Research suggests that CP and the finite work capacity (W′), can be estimated from a single 3-min bout of all-out cycling. Five experimental studies were undertaken to explore the reliability and validity of CP tests, and to propose a novel all-out testing protocol. Study one investigated the reliability and validity of the 3-min cycling test when performed against a fixed resistance and in isokinetic mode. Results suggested that the 3-min cycling test provided a reliable and valid estimate of CP in isokinetic mode, but significantly overestimated CP when performed against a fixed resistance. Study two investigated the effect of cadence on CP and W′ during the 3-min cycling test when performed against a fixed resistance, with results suggesting that a better estimation of CP is observed at higher cadences (e.g. preferred cadence +10 rev·min⁻¹). Studies three and four focused on measuring power output using cycle-mounted power meters to support the novel all-out testing protocol used in study five. The PowerTap P1 pedals demonstrated greater reliability and validity than the Garmin Vector 2 pedals across all power outputs, with reliability maintained after prolonged use. Consequently, the PowerTap P1 pedals were used in study five, which investigated the reliability and validity of a novel all-out cycling test to estimate CP and W′. Results suggested that CP could be estimated from the novel all-out cycling test; however, caution should be taken when estimating W′. The results also suggested that cycling at CP calculated from the original protocol, 3-min cycling test protocol, and novel all-out test protocol resulted in exhaustion occurring within 20 min, and a metabolic steady-state was not observed. The overall findings of this thesis question the underpinning physiology of CP, and whether CP represents the boundary between the heavy and severe exercise intensity domains.
ACKNOWLEDGEMENTS

Firstly, thanks must be given to Professor Simon Jobson who has been part of my PhD journey since the very beginning. I would not be in the position I am today without his guidance, support and honesty. Thank you, Simon. My PhD journey started in 2012, and I have worked with several supervisors throughout the process. They have all provided me with support in their own way, and I am extremely grateful to them all. Thank you, Professor Stewart Bruce-Low, Dr Helen Thomas, Dr David Jessop and Dr Michelle Jones.

Secondly, I would like to thank all the participants who volunteered to take part in my research studies. Without their help, I would not have been able to complete this thesis, and I can’t thank them enough for the time they have given me. Some of my participants completed all the studies in this thesis, and their commitment has not gone unnoticed.

I would also like to thank my colleagues at Solent University. I promise I will no longer spend our coffee breaks talking about critical power!

Finally, my family. I am so lucky to have such a supportive wife. I know that it has not been easy, and she has been on this journey with me since the very beginning. I am looking forward to spending much more time with her and our wonderful children, Rose and Evie. I love you all so much. Thank you.
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\[ t = \frac{W'}{P - CP} \]

Equation 2
Linear work-time critical power model

\[ W = CPt + W' \]

Equation 3
Linear power 1/time critical power model

\[ P = W' \left( \frac{1}{t} \right) + CP \]

Equation 4
Nonlinear 3-parameter critical power model

\[ t = \left( \frac{W'}{P - CP} \right) - \left( \frac{W'}{CP - P_{\text{max}}} \right) \]

Equation 5

\[ W'_{\text{BAL}} - W' = \int_0^t (W'_{\text{exp}}) (e^{-(t-u)/\tau W'}) \]

Equation 6

Lode Excalibur Sport’s fixed resistance

linear factor (resistance) = \[ \frac{\text{power output}}{\text{cadence}^2} \]
Equation 7

Fixed resistance used during the 3-min cycling test

\[
\text{linear factor (resistance)} = \frac{50\% \Delta}{\text{preferred cadence}^2}
\]

Equation 8

Power-time integral (work above end power)

\[
\int_a^b f(x) \, dx = \frac{b-a}{n} \left[ (y_0 + y_n) + 2(y_1 + y_2 + y_3 + \cdots) \right]
\]
MODES OF EXERCISE

During each experimental study within this thesis, the Lode Excalibur Sport was used in the following testing modes.

Hyperbolic Mode
When testing in hyperbolic mode, the workload is independent of cadence, and a predetermined workload is maintained by the ergometer when cycling between 30–150 rev·min⁻¹.

Linear Mode
The linear mode is cadence dependent, with a linear relationship observed between torque and cadence. When cycling in this mode, the higher the participant’s cadence, the higher the power output. In this mode, the participants cycle against a fixed resistance, which is set by the following equation: linear factor (resistance) = power output/cadence²

Isokinetic Mode
The isokinetic mode uses a linear relationship between power output and torque, and when testing in this mode, the participants are unable to cycle faster than the predetermined cadence.
DISSEMINATION

The following publications and conference presentations can be found in appendix a and b, respectively.

Peer-reviewed publications


Book contributions

Conference presentations


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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>50% Δ</td>
<td>50% of the difference between GET and VO\textsubscript{2peak}</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>AWC</td>
<td>Anaerobic Work Capacity</td>
</tr>
<tr>
<td>BIF</td>
<td>Best Individual Fit</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>CV</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>CP</td>
<td>Critical Power</td>
</tr>
<tr>
<td>ECG</td>
<td>Electrocardiogram</td>
</tr>
<tr>
<td>EP</td>
<td>End Power</td>
</tr>
<tr>
<td>ES</td>
<td>Effect Size</td>
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<tr>
<td>FTP</td>
<td>Functional Threshold Power</td>
</tr>
<tr>
<td>GET</td>
<td>Gas Exchange Threshold</td>
</tr>
<tr>
<td>ICC</td>
<td>Intraclass Correlation Coefficient</td>
</tr>
<tr>
<td>K\textsuperscript+</td>
<td>Potassium Ion</td>
</tr>
<tr>
<td>LoA</td>
<td>Limits of Agreement</td>
</tr>
<tr>
<td>LT</td>
<td>Lactate Threshold</td>
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<tr>
<td>MAOD</td>
<td>Maximal Accumulated Oxygen Deficit</td>
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<tr>
<td>MAP</td>
<td>Maximal Aerobic Power</td>
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<tr>
<td>MLSS</td>
<td>Maximal Lactate Steady State</td>
</tr>
<tr>
<td>MVC</td>
<td>Maximal Voluntary Contraction</td>
</tr>
<tr>
<td>P1</td>
<td>PowerTap P1 Power Pedals</td>
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<tr>
<td>PAR-Q</td>
<td>Physical Activity Readiness Questionnaire</td>
</tr>
<tr>
<td>PCr</td>
<td>Phosphocreatine</td>
</tr>
<tr>
<td>P\textsubscript{i}</td>
<td>Inorganic Phosphate</td>
</tr>
<tr>
<td>P\textsubscript{max}</td>
<td>Instantaneous Maximal Power</td>
</tr>
<tr>
<td>P\textsubscript{MRS}</td>
<td>P magnetic resonance spectroscopy</td>
</tr>
<tr>
<td>r</td>
<td>Correlation Coefficient</td>
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<tr>
<td>RER</td>
<td>Respiratory Exchange Ratio</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
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<td>------------------------------------</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
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<tr>
<td>SE</td>
<td>Standard Error</td>
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<tr>
<td>SEE</td>
<td>Standard Error of the Estimate</td>
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<tr>
<td>TEM</td>
<td>Technical Error of Measurement</td>
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<tr>
<td>TT</td>
<td>Time Trial</td>
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<tr>
<td>TTE</td>
<td>Time-to-Exhaustion</td>
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<tr>
<td>V2</td>
<td>Garmin Vector 2 Power Pedals</td>
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<tr>
<td>$\dot{V}_E$</td>
<td>Minute Ventilation</td>
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<td>$\dot{V}CO_2$</td>
<td>Carbon Dioxide Production</td>
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<td>Oxygen Uptake</td>
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<tr>
<td>VO$_2$peak</td>
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</tr>
<tr>
<td>$W'$</td>
<td>Finite Work Capacity</td>
</tr>
<tr>
<td>WAnT</td>
<td>Wingate Anaerobic Test</td>
</tr>
<tr>
<td>WEP</td>
<td>Work Done above End Power</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organisation</td>
</tr>
<tr>
<td>WIF</td>
<td>Worst Individual Fit</td>
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1 GENERAL INTRODUCTION

The foundations of our current understanding of exercise physiology can be credited to Nobel Prize Laureate, A.V. Hill, whose research during the early twentieth century focused on muscle physiology, including the role of lactic acid, oxygen kinetics and the utilisation of oxygen during exercise. Hill was the first to demonstrate that there is a linear relationship between oxygen uptake ($V\dot{O}_2$) and running speed. Additionally, it was suggested that $V\dot{O}_2$ will eventually reach a maximum value, irrespective of an increase in work rate, with this observation point defined as the maximum oxygen uptake ($V\dot{O}_{2\text{max}}$) (Hill and Lupton 1924).

Exercise physiology is now an established field of study throughout the world with research often focused on endurance sports such as running, rowing and cycling (McArdle, Katch and Katch 2014).

Cycling is commonly associated with an abundance of training data, possibly due to the relative ease of collecting real-time information about performance from cycle-mounted power meters (e.g. heart rate, speed, power output and cadence) (Jeukendrup, Craig and Hawley 2000). The popularity of cycling has increased the demand for cycling products such as the power meter, resulting in a reduction in price and more accessibility to all levels of athlete. It is now common for cyclists of all standards to use training monitors in combination with data collected from laboratory-based physiological tests to help inform training sessions (Allen and Coggan 2012). Athletes and coaches frequently utilise laboratory-based exercise testing protocols to set training zones, monitor performance changes, and to identify an athlete’s strengths and weaknesses (Davison and Bird 1997, Paton and Hopkins 2001, Faude, Kindermann and Meyer 2009, Sperlich et al. 2011). There are numerous testing protocols available that can be included in a battery of tests when monitoring the physiological condition of a cyclist, with examples including the lactate threshold (LT) protocol, maximal lactate steady-state (MLSS) protocol, and $V\dot{O}_{2\text{max}}$ protocol (Jobson and Irvine 2017); however,
despite their popularity, each has its limitations. Firstly, it is common for these protocols to be restricted to a laboratory environment, especially for protocols such as the VO2max, where the use of specialist equipment is required. Secondly, protocols such as the LT, require specialist expertise to accurately establish individual thresholds, with several methods of analysis used in the literature. These include visual inspection (Goodwin et al. 2007), fixed blood lactate values (e.g. the onset of blood lactate accumulation = 4 mmol·L⁻¹) (Heck et al. 1985), and mathematical methods (e.g. Dmax) (Czuba et al. 2009), and some concerns have recently been raised about the differences that are likely to occur if directly comparing methods (Jamnick et al. 2018). Finally, some testing protocols (e.g. MLSS) require multiple visits to the laboratory, which is not favoured by athletes or coaches due to the disruption this causes to a training programme (Iannetta et al. 2018).

An alternative test to those introduced above is the critical power (CP) protocol, which has received much attention over the past fifty years it has been suggested that CP represents the highest power output where a steady-state response in VO₂ and blood lactate is observed (Jones et al. 2010). The CP concept can be traced back to the early twentieth century when Hill (1925) plotted current world record times during endurance events, with a plateau in average speed observed as the race duration was increased. This observation was later described using mathematical modelling by Monod and Scherrer (1965) with the asymptote of a power-duration relationship defined as CP, and the curvature constant originally termed the anaerobic work capacity, but now more commonly known as a finite work capacity (W'). It has been suggested that the CP concept is beneficial to athletes, coaches and researchers as it can be calculated using equipment which is commonly used by cyclists (e.g. a power meter and an accurate measure of time). It can also provide information about both the anaerobic and aerobic energy systems from a single testing protocol, which potentially provides an advantage over alternative protocols (Hopker and Jobson 2012). The ability to
monitor both anaerobic and aerobic parameters from a single protocol is appealing in an applied setting; however, like the MLSS testing protocol, multiple testing sessions are required to calculate CP and $W'$ accurately.

Based on the time-consuming nature of the original CP testing protocol, several researchers have investigated the possibility of estimating CP and $W'$ from a single all-out testing protocol (Burnley, Doust and Vanhatalo 2006, Vanhatalo, Doust and Burnley 2007, Bergstrom et al. 2012, McClave, LeBlanc and Hawkins 2011, Clark, Murray and Pettitt 2013, Karsten et al. 2014). The original all-out testing protocol can be credited to Burnley, Doust and Vanhatalo (2006) who hypothesised that peak oxygen uptake ($\dot{V}O_{2\text{peak}}$), and the power output at MLSS, could be estimated from a single 3-min all-out cycling test. Subsequently, the 3-min cycling test was demonstrated to provide a valid estimation of CP by Vanhatalo, Doust and Burnley (2007), with the authors concluding that the 3-min cycling test provides a practical alternative to the original protocol, which, in comparison, requires multiple testing visits to calculate CP. Since the 3-min cycling test was introduced, several authors have questioned the validity of the testing protocol, concluding that it significantly overestimates CP and underestimates $W'$, with suggestions that the ergometer, testing mode, and participant fitness may all affect its validity (McClave, LeBlanc and Hawkins 2011, Karsten et al. 2014, Dicks et al. 2016).

Deciding which physiological tests to include in a testing battery often depends on the associated costs, equipment requirements, reliability, validity, and duration of testing protocols (Turner et al. 2011). Despite the suggestion that the original CP testing protocol is reliable, valid, and allows endurance fitness to be monitored using minimal equipment, this protocol is not frequently used in applied sports science due to the number of testing sessions involved, combined with its perceived mathematical complexity (Vanhatalo, Jones
and Burnley 2011). The original research by Vanhatalo, Doust and Burnley (2007) appears to overcome these limitations, providing a practical testing protocol to estimate both CP and \( W' \) from a single testing session. With some recent concerns raised about the reliability and validity of the original 3-min cycling test, research has continued to focus on the application of ‘all-out’ testing protocols in the determination of both parameters from the power-duration relationship initially described by Monod and Scherrer (1965). Therefore, the overall aim of this thesis was to investigate the reliability and validity of single-day testing protocols to estimate CP and \( W' \).
2 REVIEW OF LITERATURE

2.1 Physiological Testing for Cyclists

Before utilising laboratory-based testing to monitor and inform training, it is essential to understand the physiological determinants of cycling performance. The schematic developed by Joyner and Coyle (2008) highlights that endurance performance is dependent on aerobic performance, anaerobic performance and gross mechanical efficiency (Figure 2.1).

![Figure 2.1 The physiological determinants of endurance performance (JOYNER, M.J. and E.F. COYLE, 2008, The Journal of Physiology, 586(1), 35–44).](image)

Based on the physiological determinants of endurance exercise, there are numerous testing protocols available to an athlete, coach and sports scientist that could be implemented into a testing battery. It is common for a testing battery to be completed at regular intervals throughout a season; however, a sports scientist or coach must deal with constraints including injuries, athlete motivation, insufficient time and disruption of specific training sessions, which may all limit the implementation of a testing session (Bishop 2008).
Therefore, shorter testing sessions that can provide informative data are often favoured by athletes and coaches. Laboratory-based testing sessions are typically focused on gaining an understanding of an athlete’s anaerobic capacity and aerobic power (Allen and Coggan 2012), and some of the most commonly utilised testing protocols are outlined below.

2.1.1 Wingate Anaerobic Test

Anaerobic capacity is defined as the capacity of ATP-PCr and anaerobic glycolysis to resynthesise ATP during maximal exercise (Bogdanis et al. 1996, Kenney et al. 2015). As a consequence of the difficulty in directly measuring ATP resynthesis during anaerobic exercise, anaerobic work capacity (AWC), which is defined as the total amount of work performed during an exhaustive test (Bar-Or 1987), is often used as an alternative to anaerobic capacity (McArdle, Katch and Katch 2010). One of the most established laboratory-based testing protocols for measuring AWC is the Wingate Anaerobic Test (WAnT) (Green and Dawson 1993, Zupan et al. 2009). The WAnT is a 30-s maximal sprint test on a cycle ergometer which allows the determination of peak power output, mean power output, fatigue index and AWC (Clark, Wagner and Heath 2018). The WAnT produces high test-retest reliability with an intraclass correlation coefficient (ICC) of 0.90–0.97, and consequently remains a commonly performed testing protocol within sports science (Bar-Or 1987, Hachana et al. 2012, Attia et al. 2014), whilst also being the criterion measure against which other anaerobic testing protocols are validated (Zagatto et al. 2017). The WAnT is typically used as part of a battery of tests to monitor performance changes (Zupan et al. 2009) and has been shown to correlate with mountain bike performance times ($r = –0.79$, Inoue et al. 2012), and the average power output relative to body mass observed during the test has been suggested to predict cycling hill climbing performance ($r = –0.89$, Davison et al. 2000).
2.1.2 Maximal Oxygen Uptake

Maximal oxygen uptake (\(\dot{V}O_{2\text{max}}\)) is defined as the highest rate of oxygen uptake (\(\dot{V}O_2\)) that can be taken in by the body and utilised by the working muscles, and is regarded as the “gold standard” for measuring aerobic capacity (Bassett and Howley 2000). A variety of laboratory-based ergometers (e.g. stationary cycle ergometer, turbo-trainer, treadmill), and methods of indirect calorimetry (e.g. Douglas bag and metabolic cart) allow for the determination of \(\dot{V}O_{2\text{max}}\); however, laboratory measures require specialist equipment and knowledge to complete the test and analyse the results accurately. Typically, a \(\dot{V}O_{2\text{max}}\) test uses an incremental ramp protocol which is designed to exhaust the athlete within 8–12 min (Poole and Jones 2017). The \(\dot{V}O_{2\text{max}}\) ramp protocol has been demonstrated to be highly reliable (ICC = 0.91) (Hall-Lopez et al. 2015) and has been shown to correlate to endurance performance \((r = –0.78, \text{Butts, Henry and McLean 1991}; r = 0.78, \text{de Souza et al. 2014})\). The presence of a plateau in \(\dot{V}O_2\) is often used as one of the criteria for determining \(\dot{V}O_{2\text{max}}\), requiring individuals to be highly motivated and capable of exercising to volitional exhaustion (Poole and Jones 2017). Despite the continued use of this criterion in sports science research, concerns have been raised due to the relatively infrequent occurrence of this plateau (Midgley and Carroll 2009). To overcome this concern, the term \(\dot{V}O_{2\text{peak}}\) is often used within the literature to instead refer to the highest \(\dot{V}O_2\) observed during a particular testing session (Poole and Jones 2017).

2.1.3 Lactate Threshold Test

The lactate threshold (LT) test is one of the most commonly performed laboratory-based testing protocols in sports science (Faude, Kindermann and Meyer 2009). The LT testing protocol uses capillary blood sampling from the fingertip or earlobe to allow the plotting of blood lactate levels against increasing speed or power output. The LT test allows the determination of two key thresholds: the lactate threshold, which represents the initial rise in blood lactate from baseline values (>0.4 mmol·L\(^{-1}\)), and the lactate turnpoint, represented
by a sharp increase in blood lactate leading to exhaustion (Eston and Reilly 2009). There has been some criticism of the LT testing protocol over the last ten years due to the range of methods used during data analysis, primarily because the determination of both thresholds relies on human interpretation (Faude, Kindermann and Meyer 2009, Valenzuela et al. 2018). Nonetheless, the LT test is commonly used in applied sports science, has been demonstrated to have excellent test-retest reliability in competitive cyclists (ICC = 0.94) (Hoefelmann et al. 2015), is sensitive to relative changes in fitness (Beneke, Leithauser and Ochentel 2011) and has been shown to predict 1 h time-trial (TT) performance ($r = 0.89$) (Lorenzo et al. 2011).

A non-invasive alternative to the LT test is the gas exchange threshold (GET), with both thresholds often used interchangeably when defining exercise intensity domains. The GET uses linear regression analysis of $\dot{V}O_2$ and $\dot{V}CO_2$ measured during incremental exercise to detect the point at which there is an excess in $CO_2$, which can be explained by the buffering of hydrogen ions ($H^+$) (Beaver, Waseserman and Whipp 1986). It has been suggested that GET provides a non-invasive measure of LT, with no significant difference observed between each measure ($1.79 \pm 0.54 \text{ L}\cdot\text{min}^{-1}$ vs. $1.83 \pm 0.51 \text{ L}\cdot\text{min}^{-1}$, respectively) (Thin et al. 2002). Additionally, it has also been suggested that work rates associated with GET and MLSS are significantly correlated ($r = 0.93$) (Dekerle et al. 2003). Despite the GET being a non-invasive alternative to the LT test, the testing protocol requires access to a metabolic cart, which may result in its exclusion from routine measurement in sports science.

2.1.4 Functional Threshold Power

Following the completion of a maximal 20-min TT, functional threshold power (FTP) is calculated as the average power output observed, minus 5% (Miller, Moir and Stannard 2014). An individual’s FTP represents the highest power output that can be sustained for 60 min, but due to the physiological and psychological challenges of completing a 60-min maximal TT-based effort, Allen and Coggan (2012) suggested using a shorter, 20-min TT to
estimate FTP. The authors found that in their experience, subtracting 5% of the average 20-min power output provided a very close estimation of the individual’s maximum 60-min power output. These observations have recently been questioned by Borszcz et al. (2018), who concluded that participants were only able to cycle for approximately 50 min at FTP estimated from a 20-min test, with the authors suggesting that some caution should be taken when using FTP to inform training sessions. These results may be explained by the suggestion that the subtraction factor needs to be individualised, and rather than subtracting 5%, some athletes may need to subtract 2–8% of their 20-min power output (Allen and Coggan 2012). Despite some concerns about the physiological basis of the FTP test, it has been shown to strongly correlate to LT in trained cyclists ($r = 0.77$, Valenzuela et al. 2018).

2.1.5 Maximal Lactate Steady State
The maximal lactate steady state (MLSS) test provides an assessment of the highest exercise intensity that will result in a steady-state production of blood lactate (Kilding and Jones 2005) and is often regarded as the “gold standard” for the evaluation of endurance performance (Czuba et al. 2009, Faude, Kindermann and Meyer 2009, Grossl et al. 2012). The MLSS testing protocol requires approximately 4–7, 30-min steady-state exercise tests to be completed on separate days. During each laboratory visit, if an increase in blood lactate is observed during the 30-min test, a repeat test at a slightly lower intensity is performed in the next visit, with this process continued until the maximal intensity resulting in a steady-state response is identified. The MLSS has been suggested to have excellent test-retest reliability (ICC = 0.98, Hauser et al. 2013) and has been successfully used for prescribing training (Philp et al. 2008). The power output observed at MLSS has also been shown to correlate to endurance performance, with suggestions that it can be used to predict cycling TT performance (Grossl et al. 2012). The time-consuming nature of the protocol often excludes it from a typical athlete’s testing battery, despite evidence to suggest that the MLSS test can result in training and performance related improvements (Keir et al. 2015).
2.1.6 Critical Power Test

It has been suggested that critical power (CP) shares a similar physiological underpinning to MLSS, resulting in the highest sustainable power output where a steady-state response in blood lactate and $\dot{V}O_2$ is observed (Mattioni Maturana et al. 2016). CP was originally described as a power output that could be maintained without fatigue and was derived from the asymptote of a nonlinear power-duration relationship (Monod and Scherrer 1965). Using mathematical modelling, two parameters can be determined: an aerobic component, which is rate- but not capacity-limited (CP), and an anaerobic component, which has a finite capacity, but is not rate-limited ($W'$) (Jones et al. 2010). One of the main benefits of the CP test is that it provides the athlete and coach with information about the anaerobic and aerobic systems from a single testing protocol (Hopker and Jobson 2012). CP testing is also regarded as an attractive alternative to MLSS testing (Dekerle et al. 2003) due to its non-invasive protocol, and the ability to complete testing using a standard road bike and power meter. In addition, the calculation of CP and $W'$ does not rely on human interpretation, which provides an advantage over the LT testing protocol. CP testing provides excellent test-retest reliability (ICC = 0.94, Triska et al. 2017) and has been demonstrated to accurately predict 16.1 km TT performance ($r = -0.83$, Black et al. 2014). Similar to the MLSS testing protocol, the original CP protocol requires several testing sessions, which often discourages coaches from utilising this test throughout the season (Broxterman et al. 2012). The CP concept is reviewed in more detail in section 2.3.

2.2 Exercise Intensity Domains

Building on the work of Whipp and Wasserman (1972), it is common to refer to four exercise intensity domains to define the physiological responses to exercise (Figure 2.2); termed moderate, heavy, severe and extreme (Poole 2009, Burnley and Jones 2016), with each
defined by the unique responses of VO$_2$ and blood lactate observed during exercise (Poole 2009) (Figure 2.3).

The demarcation between each exercise intensity domain can be established from a variety of physiological testing sessions including the GET, LT, CP and VO$_{2\text{max}}$. It is widely accepted that the demarcation between the moderate and heavy exercise intensity domains is defined by the LT or GET (Jones et al. 2010), with the demarcation between the heavy and severe exercise intensity domains defined by CP (Poole 2009) (Figure 2.3).

Figure 2.2 An example of the power-duration relationship depicting the moderate, heavy, severe and extreme exercise intensity exercise domains (POOLE, D.C, 2009, Experimental Physiology, 94(2), 197–198).
2.2.1 Moderate Exercise Intensity Domain

At the onset of exercise below LT/GET, blood lactate concentrations may initially rise temporarily but will quickly return close to resting values if exercise is maintained within the moderate exercise intensity domain (Ferguson et al. 2018). It is not until exercise rises above this threshold (i.e. within the heavy exercise intensity domain) for an extended duration that the onset of metabolic acidosis, and ultimately fatigue ensues (Gaesser and Poole 1996, Davis et al. 2007). The physiological response from rest to moderate intensity exercise has been established within the literature, and at the onset of exercise, an increase in cardiac output results in a short time delay of approximately 15 s (Phase I), followed by an exponential rise in VO₂ (Phase II), until steady-state is achieved within 2–3 min (Carter et al. 2002, Wilkerson et al. 2004, Burnley and Jones 2016) (Figure 2.3). Exercise within the moderate exercise intensity domain is met almost exclusively by aerobic metabolism, resulting in an intensity that is sustainable for several hours (Faude, Kindermann and Meyer 2009). The fatiguing mechanisms of exercising within the moderate exercise intensity

Figure 2.3 VO₂ responses to exercising in the moderate, heavy, severe and extreme exercise intensity domains (WILKERSON, D.P. et al., 2004, Respiratory Physiology and Neurobiology, 142(2–3), 211–223 and POOLE, D.C. and JONES, A.M. 2012, Comprehensive Physiology, 2(2), 933–996).
domain are rarely studied in detail; potentially due to duration it takes to reach exhaustion in this domain, which for some individuals, may take several hours. It has been suggested, however, that the growing popularity of ultra-endurance events has provided a platform for gaining an understanding into the fatiguing processes during exercise of greater than 2 h (Burnley, Vanhatalo and Jones 2012). A study by Lepers et al. (2002) investigated the fatiguing mechanisms during a 5-h cycling test and suggested that the muscle contractile properties are significantly changed within 60 min of exercise, followed by a potential impairment of central fatigue. The mechanisms of neuromuscular fatigue have also been studied in ultra-endurance running with maximal voluntary contractions of the knee extensors measured before and after a 24-h running test (Martin et al. 2010). The results suggested that there was a significant loss in maximal voluntary contraction (MVC) and the authors also suggested that a central fatigue mechanism is observed during ultra-endurance exercise. The results of these studies should be used with some caution, with Burnley et al. (2012) arguing that the authors do not confidently explain the limits of performance within the moderate exercise intensity domain as both protocols used fixed distances/durations. To overcome this limitation, it was suggested that testing protocols need to be completed to volitional exhaustion to further our knowledge of the fatiguing mechanisms within the moderate intensity exercise domain. The training adaptations to exercising within this domain include an increase in muscle capillary density and haemoglobin content (Joyner and Coyle 2008).

2.2.2 Heavy Exercise Intensity Domain

When exercising within the heavy exercise intensity domain, there is a 10–20 min delay in VO$_2$ steady-state due to the presence of the VO$_2$ slow component (Gaesser and Poole 1996, Burnley and Jones 2016). The VO$_2$ slow component results in both VO$_2$ and blood lactate stabilising at a higher steady-state than would be expected when exercising during the moderate exercise intensity domain (Burnley et al. 2012). With CP demarcating the upper
boundary of the heavy domain, it is assumed that CP represents the highest power output associated with a metabolic steady-state. Exercising within the heavy exercise intensity domain should result in a steady-state response of $\dot{V}O_2$ and blood lactate, with suggestions that fatigue may occur within this domain as a result of muscle glycogen depletion (Joyner and Coyle 2008). It has also been suggested that fatigue within this domain occurs as a result of increased fatiguing metabolites resulting in homeostatic failure within the working muscles (Baron et al. 2008) and, more recently, Burnley et al. (2012) demonstrated that peripheral fatigue does develop below CP, albeit at a very slow rate. The training adaptations to exercising within the heavy exercise intensity domain are likely to include an improved LT and an increase in muscle glycogen storage (Holloszy and Booth 1976, Allen and Coggan 2012).

### 2.2.3 Severe Exercise Intensity Domain

It has been documented that exercising in the severe exercise intensity domain (i.e. above CP), results in a power output where steady-state is not achieved, and $\dot{V}O_{2\text{max}}$ is attained (Poole et al. 1988). More recently, however, Sawyer et al. (2012) found that $\dot{V}O_2$ is not necessarily driven to its maximum when completing time-to-exhaustion (TTE) tests within the severe exercise intensity domain. The authors concluded that exercising 10–36 W above CP resulted in a $\dot{V}O_2$ which was significantly lower than the traditional incremental ramp test protocol $\dot{V}O_{2\text{max}}$ (3.1 ± 0.8 L·min$^{-1}$ vs. 3.6 ± 0.9 L·min$^{-1}$, respectively). The true explanation for task failure within the severe intensity domain remains unclear, but it has been reported in a recent study by Burnley and Jones (2016) that failure may occur due to a limit in pain tolerance or lack of motivation. This explanation may help to explain why the participants in the study by Sawyer et al. (2012) did not attain $\dot{V}O_{2\text{max}}$ when cycling just above CP; however, despite these suggestions, Burnley and Jones (2016) concluded that the reason for task failure should be investigated through an understanding of bioenergetics and neuromuscular physiology rather than purely psychological reasons. Training within the severe exercise
intensity domain is likely to result in an increase in stroke volume, maximal cardiac output and \( \dot{V}O_{2\text{max}} \) (Helgerud et al. 2007, Astorino et al. 2016).

### 2.2.4 Extreme Intensity Domain

It has been suggested that exercising above the severe exercise intensity domain (i.e. above \( \dot{V}O_{2\text{max}} \)) presents a unique physiological response and, therefore, an additional domain may be used within the literature (Wilkerson et al. 2004). This domain has been defined as extreme and is typically represented by an intensity where exhaustion occurs before \( \dot{V}O_{2\text{max}} \) is attained (Figure 2.3). Despite limited research on the mechanistic basis of the extreme exercise intensity domain, it is suggested that it differs physiologically to the severe exercise domain and the two domains should be investigated separately (Burnley and Jones 2016). Due to the high power output and short duration of training within the extreme intensity domain, training adaptations include hypertrophy of fast twitch muscle fibres and an increase in neuromuscular power (Allen and Coggan 2012).

### 2.3 The Critical Power Concept

The CP concept can be traced back to the early twentieth century when Hill (1925) plotted world record performance times for bicycling, speed-skating, running, and walking against the average speed for each duration. A nonlinear relationship between velocity and time was observed, and it was suggested that speed would reach a plateau if the distance were increased (Figure 2.4). It was explained by Hill (1925) that elite athletes of this time did not concentrate on distances above 10 miles and suggested that the record times were unlikely to be an accurate reflection of human capabilities at these distances (e.g. 10–100 miles). Given the concerns about the record times above 10 miles, it was suggested that the true asymptote of the velocity-time relationship for running would lie somewhere between the dashed lines B and C displayed in Figure 2.4.
Figure 2.4 The original plot of performance times and average speed for speed-skating, running, bicycling and walking (HILL, A.V. 1925, *Nature*, 2919(116), 544–548).

To further highlight the velocity-time relationship, a plot can be made using the current world record times for all key distances from 100 m to a marathon (Figure 2.5). Interestingly, a clearer asymptote is observed from this plot than the original by Hill (1925), which may suggest that the current record for marathon distance is at the edge of human capability.

Figure 2.5 Current world records for 100 m, 200 m, 400 m, 800 m, 1 km, 1.5 km, 2 km, 3 km, 5 km, 10 km, Half-marathon and Marathon.
The hyperbolic relationship between work and the time-to-exhaustion was initially explained using mathematical models by Monod and Scherrer (1965) and is commonly referred to as the power-duration relationship. The asymptote of this relationship is termed CP and theoretically defined as the highest work rate that could be maintained without fatigue. The curvature constant of the power-duration relationship was originally termed the anaerobic work capacity (AWC) but is now more commonly referred to as the finite work capacity ($W'$) (Jones et al. 2010). Additional detail on the finite work capacity can be found in section 2.5.

Typically, the original CP protocol requires 3–8 TTE cycling tests, with each being carried out on separate days (Gaesser and Wilson 1988, Poole et al. 1988, Housh, Housh and Bauge 1989, Jenkins and Quigley 1990, Smith and Hill 1993, Mattioni Maturana et al. 2018). The time it takes to complete the original protocol, combined with the perceived complexity of calculating CP and $W'$, often deters athletes and coaches from including it as part of a testing battery. To overcome the mathematical concerns of the CP concept, it has been suggested that both parameters can be calculated from simple linear regression, which is accessible to many athletes and coaches with a basic understanding of mathematics (Jones et al. 2010). It is also possible to calculate CP and $W'$ from readily available training data to avoid specific testing sessions; however, due to the challenges of controlling for external variables, this method is not frequently used (Faria, Parker and Faria 2005, Bishop 2008). Due to some concerns about the impractical nature of the original CP testing protocol, modified protocols have been suggested; these are outlined in sections 2.10 and 2.11.

2.4 Mathematical Models

There are several mathematical models used in the determination of CP and $W'$ derived from the power-duration relationship. These include the nonlinear 2-parameter, nonlinear 3-parameter, linear work/time and the linear power-1/time models. Despite all models being
mathematically equivalent, it is suggested that they are not statistically equivalent, with the nonlinear 2-parameter mathematical model the most physiologically natural (Jones et al. 2010).

2.4.1 2-parameter Critical Power Model

With interest in muscular fatigue, Monod and Scherrer (1965) initially described the power-duration relationship using the nonlinear 2-parameter model (equation 1). The two parameters used in this model were 1) the CP of dynamic work and, 2) an energetic reserve, which is now more commonly known as the finite work capacity ($W'$) (Figure 2.6). The authors concluded that fatigue only occurs above a certain level (e.g. >CP) and that the physiological basis for the power-duration relationship would have applied uses.

\[ t = \frac{W'}{P - CP} \]  

(equation 1)

- $t$: time-to-exhaustion
- $W'$: finite work capacity
- $P$: power output
- CP: critical power

![Figure 2.6 Example of the nonlinear 2-parameter mathematical model. Note that CP is calculated as the power asymptote and $W'$ as the curvature constant.](image)
Figure 2.6 highlights the nonlinear relationship between power output (independent variable) and the time-to-exhaustion (dependent variable) initially proposed by Monod and Scherrer (1965). From this relationship, it is possible to calculate the asymptote (CP) and the finite work capacity ($W'$) using nonlinear least squares regression analysis. This analysis is not overly complicated but is often analysed using specialist statistical software (e.g. SPSS), limiting its use outside of research. This limitation often results in the nonlinear 2-parameter model being transformed into two linear forms, allowing the determination of CP and $W'$ from simple linear regression. The first linear equation is the work/time mathematical model with CP and $W'$ calculated from plotting the work (dependent variable) against time (independent variable). Using the linear work/time mathematical model, CP is calculated as the slope of the linear relationship with $W'$ calculated as the y-intercept (Figure 2.7).

$$W = CPt + W'$$  \hspace{1cm} \text{(equation 2)}$

- $W$ total amount of work performed
- CP critical power
- $t$ time-to-exhaustion
- $W'$ finite work capacity

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2_7.png}
\caption{Example of the linear 2-parameter power-1/time mathematical model. Note that $W'$ is calculated as the y-intercept and CP as the slope of the regression line.}
\end{figure}
The second linear equation is the power-1/time mathematical model with CP and $W'$ calculated from plotting power output (dependent variable) against the inverse of time (independent variable). Using the linear power-1/time mathematical model, CP is calculated as the y-intercept with $W'$ calculated as the slope of the linear relationship (Figure 2.8).

$$P = W' \left( \frac{1}{t} \right) + CP$$  \hspace{1cm} \text{(equation 3)}

- $P$ = power output
- $W'$ = finite work capacity
- $t$ = time-to-exhaustion
- CP = critical power

**Figure 2.8** Example of the linear 2-parameter power-1/time mathematical model. Note that CP is calculated as the y-intercept and $W'$ as the slope of the regression line.
The 2-parameter CP model aims to include physiological processes in a mathematical model, which leads to several assumptions (Hill 1993, Morton 2006):

1) The power-duration relationship is truly hyperbolic.
2) The aerobic component, CP, is limited in rate, but not capacity.
3) The anaerobic component, Wʹ, is limited in capacity, but not rate.
4) Exhaustion will occur when Wʹ is fully depleted.
5) There is no limit to the power output available at the onset of exercise.
6) Exercise will continue for infinity if the power output is lower than CP.

2.4.2 3-parameter Critical Power Model

Based on the limitations of the original 2-parameter model, Morton (1996) proposed a 3-parameter model which aimed to overcome some of the assumptions detailed in section 2.4.1. The main difference between the 2- and 3-parameter mathematical models is the introduction of the parameter, k, which ensures that the individual’s maximum instantaneous power (P_max) is considered (Figure 2.9), overcoming assumptions 1 and 5:

\[ t = \left( \frac{W'}{P - CP} \right) - \left( \frac{W'}{CP - P_{max}} \right) \]  \hspace{1cm} \text{(equation 4)}

\begin{align*}
  t & \quad \text{time-to-exhaustion} \\
  W' & \quad \text{finite work capacity} \\
  P & \quad \text{power output} \\
  P_{max} & \quad \text{maximum instantaneous power} \\
  CP & \quad \text{critical power}
\end{align*}
In theory, the 3-parameter mathematical model should result in the most accurate calculation of CP and $W'$ and is often regarded as the criterion method within the literature (Mattioni Maturana et al. 2018); however, due to the complexity of calculating CP and $W'$ from this model, it is not often used by coaches, athletes or researchers.

### 2.5 Finite Work Capacity

The curvature constant of the power-time relationship was initially associated with intramuscular energy store depletion and termed the anaerobic work capacity (AWC) (Monod and Scherrer 1965). Monod and Scherrer (1965) suggested that the depletion of the AWC played a pivotal role in the duration of tolerable exercise during incremental exercise and would ultimately result in the attainment of $\dot{V}O_{2\text{max}}$. It was proposed that the AWC represents the total work available above CP, with energy derived from adenosine triphosphate (ATP), muscle phosphocreatine (PCr) and anaerobic glycolysis (Gaesser et al. 1995). More recently, it has been suggested that the term AWC is outdated due to the small
contribution of energy from myoglobin- and haemoglobin-bound O$_2$ stores with the term ‘finite work capacity’ ($W'$) now preferred within the literature (Jones et al. 2010). Some criticism of $W'$ has been raised over the past twenty years with authors suggesting that it is inherently difficult to calculate without fully understanding its physiological basis (Gaesser et al. 1995, Dekerle et al. 2006).

Based on its physiological underpinning, $W'$ has been compared to other measures of anaerobic power, including AWC determined from the 30-s WAnT test (Bulbulian, Jeong and Murphy 1996). The results suggested that the anaerobic components determined from each test were not correlated ($r = 0.07, P = 0.72$), and the authors concluded that the CP and WAnT tests do not result in the same measure of anaerobic capacity. $W'$ has also been compared to the maximal accumulated oxygen deficit (MAOD), which has previously been suggested to be the best measure of anaerobic capacity (Noordhof, De Koning and Foster 2010). A recent study by Muniz-Pumares et al. (2017) concluded that despite a positive correlation between $W'$ and MAOD, the extent of the difference between the two parameters indicated that the underpinning physiological mechanisms are not comparable. Similarly, low correlations between $W'$ and MAOD were reported by Jenkins and Quigley (1993), questioning the link between the two measures of anaerobic capacity. Finally, with $W'$ only present at power outputs above CP, and MAOD occurring at the onset of exercise, it is difficult to see how the physiological bases of each parameter can be shared.

2.6 Physiological Determinants of CP and $W'$

Numerous studies have been conducted to gain a deeper understanding of the physiological underpinning of CP and $W'$. It has been suggested that CP is dependent on aerobic sources with a reduction observed following ischemia and hypoxia (Moritani et al. 1981). In contrast, $W'$ has been demonstrated to have an anaerobic physiological basis and can be affected by
muscle glycogen depletion, creatine supplementation, and high-intensity interval training (Jenkins and Quigley 1992, Miura et al. 2000). More recently a large correlation ($r = 0.94$) between CP and skeletal muscle capillarity has been observed providing evidence to suggest that CP is essential for aerobic function. In contrast, no correlation was found between $W'$ and muscle capillarity or fibre type (Mitchell et al. 2018).

The assumption that $W'$ has an anaerobic basis is supported by research carried out in hypoxic conditions (Townsend et al. 2017). These authors concluded that $W'$ was not affected when exercising in altitudes of up to 3,250 m, despite the presence of some form of threshold when exercising at 4,500 m. This threshold was not adequately explained by the authors and, with a decrease in $W'$ observed above 4,500 m, the data would suggest that $W'$ may indeed be affected by hypoxic conditions. In comparison, CP, which is aerobic in nature, followed a predictable decline in magnitude at increasing altitudes. Despite the results from this study supporting previous literature (Shearman et al. 2016), the authors raised concerns about the high typical error that is often associated with the measurement of $W'$ (Karsten 2014a, Karsten et al. 2016).

The effect of blood flow has also been investigated on the CP and $W'$ parameters during a constant-power handgrip test (Broxterman et al. 2014). Based on the theory that the muscle duty cycle (time under tension/contraction time) restricts blood flow, Broxterman et al. (2014) hypothesised that higher duty cycles (i.e. greater time under tension), would restrict blood flow and, therefore, reduce CP. Assuming that $W'$ has an anaerobic physiological underpinning, the authors also hypothesised that this parameter would not change between conditions. The results concluded that the reduced blood flow observed in the higher duty cycle condition resulted in a reduction in CP because of reduced oxygen delivery. With $W'$
unchanged between the high and low duty cycle conditions, this study supported the theory that CP is aerobic in nature and that $W'$ is predominantly anaerobic.

Due to the physiological underpinnings of CP and $W'$, it has been suggested that a very high-intensity priming exercise within the severe exercise domain would alter the balance of aerobic and anaerobic energy production (Ferguson et al. 2007). Based on this hypothesis, the authors calculated CP and $W'$ with and without a 6-min supra-maximal priming exercise. The results demonstrated that the high-intensity priming exercise did not affect CP ($242 \pm 36$ W vs. $241 \pm 39$ W). In contrast, $W'$ was significantly reduced ($10.6 \pm 2.1$ kJ vs. $16.1 \pm 2.3$ kJ), suggesting that the priming exercise depleted intramuscular PCr, increasing fatigue-related metabolites such as $H^+$, inorganic phosphate ($P_i$) and potassium ions ($K^+$). The authors concluded that although the results did not explain the components of $W'$, they did suggest that the time-to-exhaustion is linked to the depletion of $W'$. The suggestion that exhaustion occurs when $W'$ is fully depleted has also been questioned using a selection of exhaustive protocols (Chidnok et al. 2013). In their study, Chidnok et al. (2013) measured $W'$ following an incremental ramp test, a 3-min all-out test, a constant work rate test, and a self-paced 3-min TT. The authors concluded that $W'$ was not different between testing protocols, with exhaustion occurring following the complete depletion of $W'$, irrespective of the protocol used. The suggestion that a depletion in intramuscular PCr would only affect the anaerobic component of the CP concept has also been investigated using a single 3-min all-out testing protocol to estimate CP and $W'$ (Vanhatalo and Jones 2009a). The authors completed a 30-s sprint either 2 or 15 min before the all-out testing protocol with results demonstrating that $W'$ is sensitive to prior exhaustive exercise and a depletion in PCr. In comparison, no significant differences were observed for CP, and the authors concluded that CP is independent of the mechanistic basis of $W'$.
Based on the suggestion that $W'$ represents the anaerobic component of the power-duration relationship, it could be argued that this parameter would increase following a period of creatine supplementation (Morton 2006). Results of a study by Miura et al. (1999) supported this theory, with $W'$ significantly increased following a 5-day period of creatine supplementation ($10.9 \pm 2.7 \text{ kJ} \text{ vs. } 13.7 \pm 3.0 \text{ kJ}$), and no change in CP. In contrast, Vanhatalo and Jones (2009b) demonstrated that neither CP or $W'$ changed following a 5-day period of creatine supplementation; however, it should be noted that in the study by Vanhatalo and Jones (2009b), CP and $W'$ were estimated from a single all-out testing protocol and it was suggested that this protocol might not have been sensitive enough to detect changes in $W'$. A detailed review of the all-out testing protocol used in the study by Vanhatalo and Jones (2009b) can be found in section 2.10.

Training studies have also been completed to increase knowledge of the physiological underpinning of CP and $W'$, with suggestions that CP increases following 6 weeks of either continuous or interval training (Gaesser and Wilson 1988). The study by Gaesser and Wilson (1988) also concluded that training did not elicit a change in $W'$ for either training group despite the raw data suggesting that $W'$ may have increased following interval training and decreased following continuous training. These results were explained by the suggestion that $W'$ demonstrated much greater variation than CP, and the observed results may be a result of modelling artefact. Interestingly, it was subsequently proposed that the $W'$ parameter significantly increases following an 8-week high-intensity training intervention (Jenkins and Quigley 1992). The authors concluded that the apparent anaerobic improvements might have been the result of an increase in glycogenolysis, coupled with an increased ability to buffer the rise in acidosis.
There remains some debate about the true physiological underpinning of $W'$ and several authors have expressed caution about using this parameter in an applied setting (Fukuba et al. 2003, Dekerle et al. 2014, Karsten et al. 2014b). Demonstrating support for the use of $W'$ during training and racing, a mathematical model has been proposed that quantifies the remaining $W'$ during intermittent exercise (Skiba et al. 2012). The mathematics used may be perceived to be complex (equation 5); however, it has been suggested that this model could be incorporated in a bike head-unit to provide real-time feedback to an athlete, enabling race strategy to be informed.

$$W'_{\text{BAL}} - W' = \int_0^t (W'_{\exp}) (e^{-\frac{(t-u)}{\tau W'}})$$

(equation 5)

$W'_{\text{BAL}}$  remaining balance of $W'$  
$W'$  finite work capacity  
$t-u$  time in seconds between intervals that result in a depletion of $W'$  
$\tau$  time constant of $W'$ reconstitution

The $W'$ balance equation was used in a study by Broxtermen et al. (2016) with participants required to complete a modified hand-grip test with alternating bouts of exercise and rest at 1.5-s intervals. Partial reconstitution of $W'$ occurred within each rest period, but it was noted that 1.5 s was not sufficiently long enough to return to resting values, which ultimately resulted in volitional exhaustion. The authors concluded that $W'$ is expended as soon as exercise increases above CP and it is also reconstituted immediately after exercise intensity drops below CP. Finally, the authors supported the theory that $W'$ depletion would result in fatigue with $W'$ fully depleted at the point of exhaustion.
The above literature demonstrates that the physiological determinants of CP and \( W' \) have been extensively studied. It is generally agreed that some confusion remains about the true physiological basis of \( W' \), with further research focusing on this parameter required.

### 2.7 Factors Affecting the Calculation of Critical Power and the Finite Work Capacity

#### 2.7.1 Number of Time-to-Exhaustion Tests

The number of TTE tests used in the calculation of CP and \( W' \) varies within the literature and typically ranges from 3–8 (Poole et al. 1988, Gaesser et al. 1995, Coats et al. 2003, Vanhatalo, Doust and Burnley 2007, Bergstrom et al. 2014, Karsten et al. 2014a, Mattioni Maturana et al. 2018). It has been suggested that increasing the number of TTE tests minimises the impact of any single test, and subsequently reduces measurement error (Mattioni Maturana et al. 2018). The impact this may have on the athlete’s motivation, however, should not be underestimated, and a compromise may be needed to ensure that the reliability and validity of the original CP testing protocol are not affected (Bartram et al. 2017). Recently, it has been demonstrated that CP and \( W' \) can vary by approximately 20 W and 6.0 kJ, respectively, when comparing protocols that used between 2 and 5 TTE tests (Mattioni Maturana et al. 2018). Despite the suggestion that increasing the number of TTE tests will result in the most accurate calculation of CP and \( W' \), it is not uncommon for 3 TTE tests to be used in applied research (Monod and Scherrer 1965, Brickley, Doust and Williams 2002, Karsten et al. 2014a, Coakley et al. 2017). This decision has recently been supported by Bartram et al. (2017) who concluded that using 3 TTE tests to calculate CP and \( W' \) resulted in a low measurement error for both parameters (~5 W and 2.0 kJ, respectively). Additionally, Mattioni Maturana et al. (2018) concluded that it might be possible to accurately estimate both parameters using only 2 TTE tests, which the authors suggested would provide a time-efficient option.
2.7.2 Duration of Each Time-to-Exhaustion Test

Another factor that can affect the calculation of CP and $W'$ is the duration of each TTE test, with Jones et al. (2010) stating that tests outside the range 2–15 min should be avoided. It has been suggested that excessively short durations should also be avoided, where fatigue occurs before $\text{VO}_{2\text{max}}$ is attained (Hill, 1993). Additionally, it has been suggested that TTE tests longer than 15 min should be avoided due to the high levels of motivation required during longer tests (Poole et al. 1988). In contrast, it has been suggested that increasing the duration of one of the TTE tests to 20 min may provide the most accurate calculation of CP and $W'$ (Mattioni Maturana et al. 2018).

Bishop, Jenkins and Howard (1998) investigated the effect of TTE test duration on the calculation of CP using the linear power-1/time model. Each participant completed five TTE tests, and CP was calculated using the lowest three power outputs ($\text{CP}_{\text{low}}$: TTE = 193–485 s), the highest three power outputs ($\text{CP}_{\text{high}}$: TTE = 68–193 s), and a range of power outputs ($\text{CP}_{\text{range}}$: TTE = 68–485 s). The authors reported that CP was significantly different across each condition, with suggestions that the lowest three power outputs would provide the most accurate calculation of CP ($\text{CP}_{\text{low}} = 164 \text{ W}$, $\text{CP}_{\text{range}} = 176 \text{ W}$, and $\text{CP}_{\text{high}} = 201 \text{ W}$). Furthermore, the results suggested that $W'$ was also affected by TTE test duration with a significant difference observed between each condition ($\text{CP}_{\text{low}} = 17.6 \text{ kJ}$, $\text{CP}_{\text{range}} = 12.8 \text{ kJ W}$, and $\text{CP}_{\text{high}} = 9.8 \text{ kJ}$). More recently, Mattioni Maturana et al. (2018) carried out a similar study but used a wider range of times for the TTE tests (1–20 min). In line with the results reported by Bishop, Jenkins and Howard (1998), this study reported that the TTE test durations had a significant effect on the calculation of CP and suggested that CP was lowest when selecting the longer TTE tests. The authors concluded that using TTE tests that were all under 12 min significantly overestimated CP and underestimated $W'$, recommending that two tests should range between 7 and 20 min.
Sections 2.7.1 and 2.7.2 demonstrate that CP and $W'$ are both affected by the number and duration of TTE tests used during a testing protocol, highlighting the importance of selecting the most appropriate testing protocol before results can be utilised in an applied setting. This is of importance where comparisons are made between athletes and different testing laboratories.

### 2.7.3 Mathematical Model

The parameters of the power-duration relationship, CP and $W'$, can be calculated from five mathematical models (Mattioni Maturana et al. 2018). The seminal work by Monod and Scherrer (1965) used the nonlinear 2-parameter model to calculate CP and $W'$; however, the linear power-1/time mathematical model has been more commonly used in recent studies, likely due to the ease of calculation from simple linear regression (Vanhatalo, Doust and Burnley 2008b, Karsten et al. 2014a, Triska et al. 2015, Kordi et al. 2018, Mitchell et al. 2018).

It has previously been explained that the five mathematical models are not statistically equivalent, and to test this hypothesis, Bergstrom et al. (2014) compared the calculation of CP and $W'$ using each model. It was concluded that each of the five mathematical models resulted in a different value for CP and $W'$, with the authors suggesting that the nonlinear 2- and 3-parameter mathematical models would provide the most accurate calculation of both parameters (Table 2.1).

<table>
<thead>
<tr>
<th>Mathematical Model</th>
<th>CP (W)</th>
<th>$W'$ (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear 3-parameter</td>
<td>174 ± 41</td>
<td>15.2 ± 5.6</td>
</tr>
<tr>
<td>Nonlinear 2-parameter</td>
<td>176 ± 49</td>
<td>14.6 ± 5.5</td>
</tr>
<tr>
<td>Linear work/time</td>
<td>181 ± 43</td>
<td>12.2 ± 5.8</td>
</tr>
<tr>
<td>Linear power-1/time</td>
<td>184 ± 42</td>
<td>11.4 ± 6.1</td>
</tr>
<tr>
<td>Exponential</td>
<td>198 ± 41</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 2.1 CP and $W'$ calculated from 5 mathematical models (BERGSTROM, H.C. et al., 2014, Journal of Strength and Conditioning Research, 28(3), 592–600).*
Mattioni Maturana et al. (2018) completed a similar study to compare the calculation of CP and $W'$ from each mathematical model and, similar to Bergstrom et al. (2014), the authors found that the nonlinear 3-parameter mathematical model resulted in the lowest CP value. Subsequently, the authors selected the nonlinear 3-parameter model as their criterion method for the calculation of CP and $W'$. Despite Mattioni Maturana et al. (2018) supporting the use of the nonlinear 3-parameter mathematical model, the authors also suggested that the linear 2-parameter work/time and power-1/time mathematical models may provide a valid calculation of CP and $W'$ when only 2–3 TTE tests are used. Not only does this reduce the number of testing sessions, but the requirement of simple linear regression techniques also makes these mathematical models more appealing to athletes and coaches (Dekerle et al. 2014, Karsten et al. 2014a). The literature described above highlights that the mathematical models used will affect the calculation of both CP and $W'$. It should be noted, however, that both Bergstrom et al. (2014) and Mattioni Maturana et al. (2018) did not validate each model using a TTE while cycling at the calculated CP, basing their conclusions on which model resulted in the best fit and lowest calculation of CP. Without completing a CP validation test at the power output associated with each model, some assumptions are made about which model, if any, provides a valid calculation of CP.

The number and duration of the TTE tests used, combined with the mathematical model, will affect the calculation of CP and $W'$, and it has been suggested that a valid calculation of CP and $W'$ can be made from 2–3 TTE tests using the linear 2-parameter mathematical models (Mattioni Maturana et al. 2018). However, it is suggested that further research is still required to determine the “gold standard” protocol for calculating the parameters of the power-duration relationship. Within each experimental study of this thesis, the linear 1/time mathematical model was used as the criterion method for calculating CP and $W'$. It has been observed that this model is the most frequently used within the scientific literature and,
therefore, the decision to use this model within each experimental study would allow a direct comparison to previous literature.

2.7.4 Time-to-Exhaustion Tests vs. Time-Trials

It has been demonstrated that the calculation of CP and $W'$ is also sensitive to the type of performance tests completed, with TTE and TT tests both used in the literature (Coakley et al. 2017). TTE tests are typically performed at a percentage of an individual’s peak power output or maximal aerobic power (MAP), calculated following an incremental ramp $\dot{VO}_2$max protocol (Vanhatalo, Doust and Burnley 2007, Karsten et al. 2014a). Based on the sensitivity of CP and $W'$ to changes in TTE duration, it is vital that the optimal percentage of peak power output or MAP is selected to ensure exhaustion occurs within the desired time. This has been demonstrated by Vanhatalo, Doust and Burnley (2007), who calculated CP from five TTE tests equivalent to 70, 80, 100 and 105% $\dot{VO}_2$peak, with a final test at either 60 or 110% $\dot{VO}_2$peak. This protocol results in exhaustion occurring between 2 and 15 min for each TTE test as suggested by Jones et al. (2010). Karsten et al. (2014a) used three TTE tests equivalent to 80, 100 and 105% MAP, with the aim of exhaustion occurring between 3 and 12 min. It could be suggested that it is easier to control a TTE test which is set to a constant-power output, but this method may be sensitive to the physiological variation between participants. For example, endurance-based cyclists may be able to cycle for >15 min at 80% $\dot{VO}_2$peak, whereas sprint cyclists may only be able to cycle for <10 min. To ensure that each TTE test fits the criteria mentioned in section 2.7.2 (e.g. two tests lasting between 7 and 20 min), it may be suggested that TT tests are more suitable (e.g. 3, 7 and 12 min) as used by Karsten et al. (2014b). It has been suggested, however, that experience of TT testing is essential before using this method as pacing, especially during longer TT tests, could affect the average power output observed (Passfield and Coakley 2014).
A recent study by Coakley et al. (2017) compared the average power output observed during TTE and TT tests. During this study, participants were required to complete three TTE tests at 80, 100 and 105% MAP, each separated by 30 min. On a separate day, the participants completed three TT tests for the duration observed from each of the TTE tests. For example, if the 100% MAP TTE test lasted 7 min, the participant was asked to complete a TT for 7 min, with the aim of producing the highest average power output. The results found that average power output was higher for the TTE test when compared to the TT tests, which resulted in a higher CP, and the authors advised that TTE tests should be used in preference to TT tests when calculating CP and $W'$. In a separate study, Passfield and Coakley (2014) found no significant difference between TTE and TT performance when cycling at high intensities (e.g. 100–105% $VO_{2\text{max}}$), with differences only observed when cycling at 80% MAP. The authors concluded that participants were unable to successfully pace the TT tests at lower power outputs (e.g. 80%) resulting in a higher average power output observed from TTE rather than TT tests. The studies by Passfield and Coakley (2014), and Coakley et al. (2017) support the use of TTE tests when determining CP as these appear to result in the highest power output for each test, and in turn, the most accurate calculation of CP and $W'$.

2.8 Physiological Responses to Cycling at Critical Power

Understanding the physiological responses to cycling within each exercise intensity domain is advantageous for training design and has received much attention within the literature (Poole et al. 1988, Brickley, Doust and Williams 2002). With suggestions that CP demarcates the boundary between the heavy and severe exercise intensity domains, it has been described as the highest rate of aerobic metabolism where steady-state exercise is achieved (Hill et al. 1993). This definition is supported by Poole et al. (1988) who demonstrated that cycling at CP results in a power output where a $VO_2$ and blood lactate steady-state was observed during a 24-min test. It has also been suggested by Housh, Housh and Bauge (1989)
that CP can be sustained for 60 min with the authors concluding that CP occurs just above an individual’s LT. Upon further analysis, it was found that the group mean was only 33 min and, therefore, some questions are raised about the sustainability of cycling at CP.

The physiological responses to exercise have also been demonstrated using P magnetic resonance spectroscopy (P MRS), with suggestions that performing constant-work exercise at CP (torque) can be sustained without an increase in fatigue-related metabolites (Jones et al. 2007). During the study by Jones et al. (2007), the authors were able to take measurements of muscle metabolites during leg extension exercise, with results concluding that exercising at an intensity 10% below CP resulted in a steady-state response for PCr, pH and Pi during a 20-min test. Results also suggested that when exercising 10% above CP, volitional exhaustion ensued within 15 min, with a steady fall in PCr and pH. The authors concluded that exercising just below CP results in a power output that is sustainable without an increase in fatigue-related metabolites.

In contrast to Poole et al. (1988) and Jones et al. (2007), the sustainability of cycling at CP has been questioned using highly-trained endurance cyclists with the results suggesting that six out of the eight participants were able to cycle at CP for 30 min (Jenkins and Quigley 1990). With a mean blood lactate of 8.9 mmol·L⁻¹ observed during the final 20 min, the authors suggested that CP may overestimate the boundary between the heavy and severe exercise intensity domains. In a similar study, McLellan and Cheung (1992) concluded that only one out of fourteen participants was able to complete 30 min of cycling at CP, stating that CP overestimated a metabolic steady-state. These results were echoed by Brickley, Doust and Williams (2002) who reported that exhaustion occurred between 20 and 40 min when cycling at CP, the authors suggesting that CP was not representative of a sustainable power output. Additionally, the physiological responses to cycling at CP have been
established with recreational cyclists, for whom exhaustion occurred after approximately 27 min (Carter and Dekerle 2014).

Research into the CP concept is often related to cycling performance; however, it is possible to apply the same concept to most endurance-based sports, including running (Galbraith et al. 2011, Broxterman et al. 2012), rowing (Kennedy and Bell 2000, Kendall et al. 2011), kayaking (Manchado-Gobatto et al. 2014), and swimming (Wakayoshi et al. 1992, di Prampero et al. 2008). Similar physiological responses to those mentioned above have been found when exercising at critical velocity (running), with both Carter and Dekerle (2014), and Penteado et al. (2014) concluding that exhaustion occurs between approximately 20 and 30 min. Additionally, Bull et al. (2008) observed that critical velocity could be maintained for between 22 and 25 min when calculated from the linear mathematical models, and up to 52 min when calculated from the nonlinear 3-parameter mathematical model. Based on these results, Bull et al. (2008) suggested that irrespective of the mathematical model used, critical velocity does not demarcate the boundary between the heavy and severe exercise intensity domains in running.

Monod and Scherrer (1965) originally defined CP as a power output that could be sustained for a very long time; however, recent research suggests that exercise at CP can only be maintained for between 20 and 40 min (Brickley, Doust and Williams 2002, Carter and Dekerle 2014). Furthermore, it has recently been recommended that CP should be defined as a theoretical construct, where a metabolic steady-state is observed, and task failure is predictable (Poole et al. 2016). The research within this section highlights that the tolerable duration of cycling at CP remains unclear, raising some questions about the practical application of the CP concept.
2.9 Applying the Critical Power Concept to Training and Racing

It is common for cyclists to perform physiological testing throughout the year to establish suitable power-based training zones (Allen and Coggan 2012). Typically, the CP testing protocol is not used in an applied setting as frequently as other laboratory- or field-based testing protocols, which is possibly due to the perceived complexity of the testing protocol and analysis (Vanhatalo, Jones and Burnley 2011). Instead, the LT or FTP testing protocols are frequently used to prescribe training zones (Jones 2016), with the LT test accepted as a criterion method for measuring aerobic performance (Faude, Kindermann and Meyer 2009). However, due to the variety of methods used to detect the lactate deflection points (e.g. visual, fixed blood lactate values, mathematical modelling), some concerns have been raised about the possible error in LT calculation (Beaver, Waseserman and Whipp 1985, Davis et al. 2007, Czuba et al. 2009, Jamnick et al. 2018). Based on the different methods used for defining the LT and LTP, it is reasonable to assume that different training zones could be identified between coaches and laboratories.

The simplicity of the FTP test makes it a popular choice for athletes and coaches, especially as the protocol can be completed outside of a laboratory environment if an athlete has access to a power meter (Miller, Moir and Stannard 2014). Despite the FTP test being one of the most commonly completed protocols by cyclists, it does not have a sound physiological basis and some concerns have been raised about its accuracy at estimating the maximum 1 h power output of an athlete (Borszcz et al. 2018). Furthermore, it has been suggested that the accuracy of the FTP test relies on the athlete being experienced at completing the testing protocol and it may be more appropriate for highly-trained athletes (Valenzuela et al. 2018).

Due to some of the concerns with the LT and FTP testing protocols, it has been suggested that a coach could utilise the CP concept as the basis for prescribing individualised training
zones (Jones et al. 2010, Clarke and Skiba 2013). The CP has a clear physiological underpinning, and the calculation uses a mathematical basis, overcoming some of the limitations of the LT and FTP testing protocols. An example of how the CP test can be used in an applied setting can be found in Table 2.2, with each training zone calculated as a percentage of CP. With limited research utilising training zones calculated from CP testing, this area needs investigating before the suggested durations at each training zone can be used with confidence. Despite the potential practical applications of CP testing being highlighted, it is essential that the concerns raised in sections 2.7 and 2.8 are addressed. These include the mathematical models used to calculate CP, the number and duration of each TTE used within the model, and the tolerable duration of cycling at CP.

Table 2.2 Relationship between training zones, exercise intensity domains, tolerable durations and associated laboratory-based testing protocols (FRANCIS, J.T. et al., 2010, Medicine & Science in Sport & Exercise, 42(9), 1769–1775).

<table>
<thead>
<tr>
<th>Training Zone</th>
<th>Exercise Domain</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>Moderate</td>
<td>&gt; 180 min</td>
</tr>
<tr>
<td>Zone 2</td>
<td>Heavy</td>
<td>180–90 min</td>
</tr>
<tr>
<td>Zone 3</td>
<td></td>
<td>90–30 min</td>
</tr>
<tr>
<td>Zone 4</td>
<td>Severe</td>
<td>30–4 min</td>
</tr>
<tr>
<td>Zone 5</td>
<td>Extreme</td>
<td>&lt; 4 min</td>
</tr>
</tbody>
</table>

Laboratory-based testing protocols can provide an accurate measure of the key performance determinants for cyclists and can also be used to monitor the effectiveness of training (Jobson and Irvine 2017). It is therefore essential that the protocols used are sensitive to detect the typical within-participant variation that is likely to be observed by a particular population (Hopkins 2000a). Cyclists typically utilise endurance and interval-based training sessions, and there is evidence to suggest that CP is sensitive to both forms of training. For example, following an 8-week endurance-based training intervention, Jenkins and Quigley
(1992) reported that CP increased by 28%, with no significant differences observed between Wʹ pre- and post-training. The authors suggested that CP testing provides a practical method for monitoring performance, especially as the CP protocol does not require the potentially arbitrary calculation of thresholds, or the requirement for blood analysis. It has also been demonstrated that CP is sensitive to high-intensity interval training, with CP shown to increase by approximately 15 W following a 4-week supervised training intervention (Vanhatalo, Doust and Burnley 2008b). In a similar study, Poole, Ward and Whipp (1990) investigated the changes in CP and Wʹ following a 7-week high-intensity training intervention. Training consisted of ten, 2-min intervals at 110% of the peak power output, separated by a 2-min recovery, and was completed three times per week. Results found that CP increased by approximately 10% following the training intervention (197 ± 13 W vs. 217 ± 11 W), and unlike the study by Vanhatalo, Doust and Burnley (2008a), where Wʹ was reduced after training, Poole, Ward and Whipp (1990) found that Wʹ was unchanged following the 7-week training intervention.

To directly compare the difference between endurance and high-intensity training, Gaesser and Wilson (1988) completed a 6-week continuous, and a 6-week high-intensity training intervention. The continuous training was low intensity and consisted of 40 min cycling at 50% VO_{2peak}, with the high-intensity interval training consisting of ten, 2-min intervals at VO_{2peak}; both training interventions were completed 3 times per week. The results showed that CP was increased by approximately 13% following continuous training and 15% following interval training, with the authors also suggesting that Wʹ was not significantly changed following either training intervention. The authors concluded that there was no difference between continuous or interval training for observing changes in CP, with both interventions sensitive to monitoring improvements in performance. Based on the findings
above, CP appears to be sensitive to training adaptations and, therefore, could be included into a cyclist’s testing battery to monitor changes in performance throughout the season.

A common finding within the scientific literature is that $W'$ is not sensitive to training, which may be due to the increased variability observed with this parameter, and it is frequently reported that the measurement of $W'$ is inherently difficult (Dekerle et al. 2014, Karsten 2014a, Karsten et al. 2016, Townsend et al. 2017). The high typical error associated with the measurement of $W'$ may provide some explanation to why this parameter is often discarded within the literature.

Considering the attention that the CP concept has received within the literature, there is limited research available on the responses to training at an intensity equivalent to CP (Mcgawley 2010). In an attempt to establish the benefits of using CP to inform training, Mcgawley (2010) completed a CP-based training study. Participants were randomly assigned to one of three training groups, 1) below CP (e.g. "LT"), 2) at CP, and 3) intermittently around CP (e.g. intervals at LT and $\dot{V}O_{2max}$). Each group trained for 6 weeks, and the training groups were matched for total work, resulting in a significantly shorter total training time for the CP group. The results suggested that CP, LT, cycling economy and $\dot{V}O_{2max}$ all significantly increased following the 6-week training study for each group; however, due to the reduced training time for the CP group, training at CP was recommended.

Research has recently demonstrated that it is possible for CP to be used in the prediction of endurance performance, which provides support for the practical application of the CP concept. Black et al. (2014) investigated the practical applications of CP estimated from an all-out cycling protocol, with results suggesting that CP was significantly correlated with 16.1 km TT performance ($r = -0.83, P <0.01$). Similarly, it has been suggested that CP provides a non-invasive measure of aerobic performance with a large correlation ($r = -0.91$) to TT
performance in competitive cyclists (Smith, Dangelmaier and Hill 1999). Furthermore, it has been suggested that the historical basis of the power-duration relationship allows CP to be used in the prediction of future human records (Billat, Koralsztein and Morton 1999). Due to the mathematical underpinning of the CP concept, it is theoretically possible that the highest potential power output could be predicted for any given duration. This information could provide considerable advantages to an athlete regarding pacing strategies within TT races, with Figure 2.10 highlighting how this could be utilised by an athlete or coach in the real world.

![Figure 2.10 The CP concept being used to predict TTE duration (HOPKER, J. and S.A. JOBSON, 2012, Performance Cycling: The Science of Success).](image)

Finally, the CP concept allows a coach to evaluate the strengths and weaknesses of their athlete along the power-duration curve, and it is possible to understand the implications of improving the power output at one end of the curve on the other. For example, it is likely that a physiological response to the enhancement of an individual’s peak power output (e.g. hypertrophy of fast-twitch muscle fibres), would be a reduction in aerobic capacity (Smith, Norris and Hogg 2002).
Despite the CP concept demonstrating several benefits, the time-consuming nature of the original testing protocol often excludes its use by many athletes and coaches. Section 2.10 goes some way to providing an alternative method for the calculation of CP and \( W' \) using an ‘all-out’ testing protocol.

**2.10 The 3-min Critical Power Cycling Test**

**2.10.1 Origin**

It was proposed by Dekerle et al. (2006) that \( W' \) could be estimated from a single bout of all-out exercise lasting 90 s (Dekerle et al. 2006). The study did not focus on CP; however, the results did demonstrate that the final power output during a 90-s test was higher than CP when calculated from the linear power-1/time mathematical model. Based on these observations, Burnley, Doust and Vanhatalo (2006) extended the duration of the all-out testing protocol to 3 min, with the aim of estimating \( \text{VO}_{2\text{peak}} \) and MLSS from a single testing session. Following pilot tests, the authors observed that power output would level out after approximately 120 s, and it was anticipated that the mean power output observed in the final 30 s of the test, termed end power (EP), would result in a reliable and sustainable power output. During this test, the participants were instructed to cycle against a pre-determined fixed resistance, and to maintain the highest possible cadence throughout the duration of the test without pacing. With an ICC of 0.99 \( (P < 0.001) \), and a typical error (TE) of \( \pm 7 \text{ W} \) between testing sessions, the 3-min cycling test appeared to provide good test-retest reliability for EP. The results also suggested that EP may provide a sustainable power output, with a plateau in \( \text{VO}_2 \) and blood lactate observed during a 30-min constant-work rate test for 60% of individuals tested; however, these results should be treated with caution, with some participants only able to sustain EP for 15–24 min before reaching volitional exhaustion. The authors of this study suggested that EP calculated from a 3-min cycling test may estimate CP and, therefore, the demarcation between the heavy and severe exercise intensity domains.
It should be noted, however, that this conclusion was based on the physiological responses to cycling at EP rather than directly comparing this value to CP calculated from the original testing protocol.

Building on the research of Burnley, Doust and Vanhatalo (2006), it was hypothesised that the 3-min cycling test would provide valid estimates of both CP and W’ calculated from the original CP testing protocol (Vanhatalo, Doust and Burnley 2007). Using the linear power-1/time mathematical model as an example, \( P = W'(1/t) + CP \), if a testing session is sufficiently long enough to deplete \( W' \), then the resulting equation would be \( P = CP \) and, therefore, the power output observed after the depletion of \( W' \) must be equal to CP. Based on this assumption, Vanhatalo, Doust and Burnley (2007) suggested that a 3-min bout of all-out cycling should be long enough to fully deplete \( W' \), resulting in a plateau in power output during the final 30 s of the test. It was hypothesised that the average power output observed in the final 30 s, \( (EP) \) would be equivalent to CP. It was also hypothesised that the work done above EP \( (WEP) \), calculated as the power-time integral above EP, would provide a valid estimate of \( W' \) (Figure 2.11). Within the current scientific literature, it is assumed that the term EP refers to the estimation of CP, and the term WEP refers to the estimation of \( W' \), when calculated from the original CP testing protocol. Despite EP and CP, and WEP and \( W' \), being used interchangeably, some concerns have been raised about the validity of the 3-min cycling test to estimate CP and \( W' \), and these are outlined in section 2.10.2.

For the 3-min cycling test to provide valid estimates of both CP and \( W' \), it is vital that \( W' \) is fully depleted within the first 150 s of the testing protocol. According to Jones et al. (2010), a successful 3-min cycling test relies on several factors, including 1) that the participants need to be highly motivated and fully familiar with the testing protocol, 2) time-based feedback is removed to ensure that pacing is prevented, 3) maximum cadence and, therefore, power
output, is maintained throughout the duration of the test, and 4) there should be no decrease in VO$_2$ throughout the duration of the test, with at least 95% VO$_{2\text{max}}$ attained when compared to an independently tested ramp test VO$_{2\text{max}}$ protocol.

![Test results]

<table>
<thead>
<tr>
<th>Test results</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP</td>
</tr>
<tr>
<td>WEP</td>
</tr>
</tbody>
</table>

Figure 2.11 An example power trace observed from a 3-min cycling test. EP is identified as the average power observed in the final 30 s, which is depicted by the vertical dashed lines. WEP is calculated as the power-time integral above EP (WRIGHT, J. 2017, Measure Everything in Three Mins! In JOBSON, S.A. and D. IRVINE, 2017. Ultra-Distance Cycling: An Expert Guide to Endurance Cycling).

The original 3-min cycling test protocol (Burnley, Doust and Vanhatalo 2006, Vanhatalo, Doust and Burnley 2007, 2008a, 2008b) was completed using an electronically-braked ergometer (Excalibur Sport, Lode, The Netherlands). This ergometer has a range of testing modes, including hyperbolic, linear, fixed torque, and on some models, an isokinetic mode. The model used by Burnley, Doust and Vanhatalo (2006) did not have an isokinetic mode, and the authors stated that this led to the decision to use a fixed resistance (i.e. linear mode) to set the resistance during the 3-min cycling test. The linear mode is cadence dependent, with a linear relationship observed between torque and cadence, and when cycling in this mode, the higher the participant’s cadence, the higher the power output (Figure 2.12).
When using the linear mode, the ergometer’s resistance is fixed and needs to be established before testing. This resistance, referred to as the linear factor, is calculated using the following equation:

\[
\text{Linear factor (resistance)} = \frac{\text{power output}}{\text{cadence}^2}
\]  

(equation 6)

It was originally suggested by Burnley, Doust and Vanhatalo (2006) that the resistance should be set so that if the participant reached their preferred cadence at the end of the 3-min cycling test, the power output would be approximately 50% of the difference between GET and VO_{2peak} (50% Δ), and in the approximate region of CP. The fixed resistance during the original 3-min cycling test was therefore calculated using 50% Δ and the participants preferred cadence using the equation below:

\[
\text{Linear factor (resistance)} = \frac{50\% \Delta}{\text{preferred cadence}^2}
\]  

(equation 7)

It was anticipated that the participants would reach their preferred cadence in the final stages of the 3-min cycling test, which would equate to a power output midway between GET and VO_{2peak} (Burnley, Doust and Vanhatalo 2006). With CP suggested to lie approximately 50% of the difference between GET and VO_{2peak} (Poole et al. 1988, Jones et al. 2010), some concerns have been raised about this protocol. It is, therefore, not unreasonable to assume that using this method to calculate the fixed resistance may naturally ‘drive’ the participant to a power output that is at, or near CP (Karsten et al. 2014a). The 3-min cycling test is often referred to as a single session testing protocol, but the requirement to calculate the resistance prior to the 3-min cycling test, necessitates an additional testing session to calculate GET and VO_{2peak}. Furthermore, the linear factor used in the original 3-min cycling test protocol is unique to the Lode Excalibur Sport and cannot be directly transferred to other testing ergometers. To address these limitations, an alternative ‘all-out’ testing protocol has
been proposed using an ergometer’s isokinetic mode (Brickley et al. 2007, Dekerle et al. 2009, de Lucas et al. 2014, Karsten et al. 2014a). The isokinetic mode uses a linear relationship between power output and torque (Figure 2.13), and when testing in this mode, the participants are unable to cycle faster than the pre-determined cadence. Unlike the linear mode, the isokinetic mode is not unique to the Lode Excalibur Sport, which allows testing to be completed on other popular laboratory-based ergometers (e.g. SRM Ergometer).

Figure 2.12 The relationship between torque, power output and cadence when using the linear mode on the Lode Excalibur Sport Ergometer (Lode Excalibur Sport User Guide, 2009).

Figure 2.13 The relationship between cadence, power output and torque when using the isokinetic mode on the Lode Excalibur Sport Ergometer (Lode Excalibur Sport User Guide, 2009).

With the original testing protocol typically requiring 3–8 TTE tests to calculate CP and $\dot{W}$, it has been suggested that the 3-min cycling test provides a time-saving and practical alternative (Vanhatalo, Doust and Burnley 2007). It was anticipated that this testing protocol would be looked upon favourably, especially by athletes and coaches who have time restrictions for physiological testing sessions (Vanhatalo, Jones and Burnley 2011). Previous literature using the 3-min cycling test is highlighted in Table 2.3.
Table 2.3 A comparison of studies that have investigated the validity of the 3-min cycling test highlighting the mixed confidence in EP and WEP.

<table>
<thead>
<tr>
<th>Author</th>
<th>Participants</th>
<th>Ergometer / Mode</th>
<th>Mathematical Model</th>
<th>Number of TTE tests</th>
<th>CP (W)</th>
<th>EP (W)</th>
<th>Wʹ (kJ)</th>
<th>WEP (kJ)</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vanhatalo et al. (2007)</td>
<td>Cyclists (n = 6) Runner (n = 2) Fitness (n = 2)</td>
<td>Lode Excalibur Sport (Linear)</td>
<td>Linear work-time</td>
<td>5</td>
<td>287 ± 56</td>
<td>287 ± 55</td>
<td>16.0 ± 3.8</td>
<td>15.0 ± 4.7</td>
<td>EP measured from the 3-min cycling test was almost identical to CP calculated from the original CP protocol. WEP was similar, albeit slightly lower than Wʹ.</td>
</tr>
<tr>
<td>Dekerle et al. (2014)</td>
<td>Active (n = 9)</td>
<td>SRM (Isokinetic)</td>
<td>Linear power-1/time</td>
<td>4</td>
<td>245 ± 38 (60 rpm)</td>
<td>259 ± 40 (60 rpm)</td>
<td>16.2 ± 3.5</td>
<td>14.7 ± 3.0</td>
<td>EP did not significantly differ from CP. However, the authors raised concerns about the levels of agreement between the two parameters. It was also concluded that WEP should not be used in a practical setting.</td>
</tr>
<tr>
<td>Karsten et al. (2014a)</td>
<td>Trained Cyclists (n = 13)</td>
<td>SRM (Isokinetic)</td>
<td>Linear work-time</td>
<td>3</td>
<td>253 ± 41</td>
<td>290 ± 41 *</td>
<td>18.6 ± 4.8</td>
<td>12.5 ± 4.3 *</td>
<td>The 3-min cycling test using the SRM isokinetic mode significantly overestimated CP and underestimated Wʹ.</td>
</tr>
<tr>
<td>Bergstrom et al. (2014)</td>
<td>Cyclists (n = 2) Runner (n = 8)</td>
<td>Lode Excalibur Sport (Linear)</td>
<td>Linear work-time</td>
<td>4</td>
<td>181 ± 42</td>
<td>196 ± 49 *</td>
<td>12.2 ± 5.8</td>
<td>10.4 ± 2.6 *</td>
<td>EP significantly overestimated CP and WEP significantly underestimated Wʹ when using the nonlinear models.</td>
</tr>
<tr>
<td>Bergstrom et al. (2014)</td>
<td>Cyclists (n = 2) Runner (n = 8)</td>
<td>Lode Excalibur Sport (Linear)</td>
<td>Linear power-1/time</td>
<td>4</td>
<td>184 ± 43</td>
<td>11.4 ± 6.1</td>
<td></td>
<td></td>
<td>EP significantly overestimated CP and WEP significantly underestimated Wʹ when using the nonlinear models.</td>
</tr>
<tr>
<td>Bergstrom et al. (2014)</td>
<td>Cyclists (n = 2) Runner (n = 8)</td>
<td>Lode Excalibur Sport (Linear)</td>
<td>Nonlinear 2-parameter</td>
<td>4</td>
<td>176 ± 40</td>
<td>14.6 ± 5.5</td>
<td></td>
<td></td>
<td>EP significantly overestimated CP and WEP significantly underestimated Wʹ when using the nonlinear models.</td>
</tr>
<tr>
<td>Dicks et al. (2016)</td>
<td>Tri (n = 5) Cyclists (n = 3) Fitness (n = 4)</td>
<td>Lode Excalibur Sport (Linear and modified using %BM)</td>
<td>Nonlinear 3-parameter</td>
<td>3</td>
<td>174 ± 41</td>
<td>231 ± 57</td>
<td>9.2 ± 3.8</td>
<td>7.0 ± 3.1</td>
<td>The 3-min cycling test using %BM to determine the fixed resistance provides valid estimations of CP and Wʹ.</td>
</tr>
</tbody>
</table>

*Significantly different from CP or Wʹ calculated from the original protocol.
2.10.2 The Reliability and Validity of the 3-min Cycling Test

The results of the study by Vanhatalo, Doust and Burnley (2007) demonstrated a near-perfect relationship between CP and EP (287 ± 56 W vs. 287 ± 55 W, respectively), and a similar, albeit slightly lower, estimation of $W'$ (15 ± 4.7 kJ vs. 16 ± 3.8 kJ). It was suggested that the 3-min cycling test might provide a more convenient testing protocol to the original CP test by reducing the required number of visits to the laboratory. To investigate the reliability of the 3-min cycling test, Johnson et al. (2011) completed the protocol on separate days, with results suggesting that the 3-min cycling test provides a reliable measure of EP, with a typical error of 15 W, a coefficient of variation (CV) of 6.7%, and an ICC of 0.93. Additionally, the authors reported that WEP was less reliable with a TE of 2.86 kJ, a CV of 27.5%, and an ICC of 0.76. Interestingly, the authors concluded that the 3-min cycling test provided a reliable measure of EP when a CV of 6.7% was observed. It is important to consider this measure in combination with other statistical analyses (e.g. TE and ICC); however, the reported CV is higher than would be expected for reliability in sports science, with the upper limit of 5% frequently used (Hopkins 2000b).

To assess the robustness of the 3-min cycling test, Vanhatalo, Doust and Burnley (2008a) manipulated the cadence used to set the fixed resistance (standard = preferred cadence, low = preferred cadence –10 rev·min⁻¹, and high = preferred cadence + 10 rev·min⁻¹). The results of this study concluded that EP was unaffected by the adoption of a lower cadence; however, EP was significantly reduced by the adoption of the higher cadence (254 ± 40 W vs. 244 ± 41 W). The results also demonstrated that WEP was affected by changes in cadence with both the low and high conditions being significantly different to the standard condition (standard = 14.2 kJ, low = 16.2 kJ and high = 12.9 kJ). The authors reported that although EP was not sensitive to lower cadences, care should be taken when setting the fixed resistance to ensure that a higher than preferred cadence is not selected. To directly compare the effect of
cadence on the 3-min cycling test, Dekerle et al. (2014), evaluated the 3-min cycling test in isokinetic mode at both 60 and 100 rev·min⁻¹, reporting a 14% lower EP with the adoption of the higher cadence. This reduction in EP was attributed to the understanding that fast twitch muscle fibres are more susceptible to fatigue when pedalling at higher cadences, resulting in a faster decline in power output, which in turn produces a lower EP during the final 30 s. Vanhatalo, Doust and Burnley (2008a) also investigated the effect of pacing on the parameters EP and WEP by replacing the initial 30 s of the test with a constant-power output phase using the ergometer’s hyperbolic mode (cadence independent). Rather than instructing the participants to cycle as fast as possible for the duration of the 3-min cycling test, the participants started with a 30-s period at either 100% or 130% of the peak power output observed from an independent incremental ramp test. The results showed no significant differences between the standard test, 100% or 130% pacing test for either EP or WEP, providing evidence to suggest that the 3-min cycling test is robust in the face of pacing variation.

Based on the physiological underpinning of the 3-min cycling test, it was argued that the 3-min cycling test should accurately estimate CP and $W'$ irrespective of the testing mode or ergometer (Karsten et al. 2014a). To test this hypothesis, the authors investigated the reliability and validity of the 3-min cycling test when completed on an SRM ergometer. Karsten et al. 2014a suggested that, although providing a reliable measure of EP, the 3-min cycling test completed using the isokinetic mode resulted in an EP which significantly overestimated CP by approximately 35 W. These results were partially explained by the ability of the participants to fully deplete $W'$ when cycling in isokinetic mode, with suggestions that individuals with a higher $W'$ may need a longer testing protocol. Additionally, participant fitness levels may affect the duration in which it takes to deplete $W'$ fully, with this suggestion supported by the mean $\text{VO}_2\text{peak}$ observed in the study by Vanhatalo,
Doust and Burnley (2007) being considerably lower than that of Karsten et al. (2014a) (~56 ml·kg$^{-1}$·min$^{-1}$ vs. ~66 ml·kg$^{-1}$·min$^{-1}$, respectively). This explanation seems reasonable when taking into consideration the research by McClave, LeBlanc and Hawkins (2011) who investigated the sustainability of EP in elite cyclists. Participants were required to cycle until exhaustion at EP, and with participants reaching exhaustion within 14 min, the authors suggested that the 3-min cycling test may overestimate CP in elite cyclists. With participant fitness potentially affecting the validity of the 3-min cycling tests, some consideration needs to be given to the participants used within each study. It is fairly common within sports science research to use recreationally trained participants from a range of sporting backgrounds, possibly due to the ease of recruiting participants from a typical student population. Given the likely physiological differences between participants of varying fitness, care should be taken when applying the practical recommendations from a study completed using recreationally training participants, to a group of trained or elite cyclists.

The 3-min cycling test has also been directly compared to the linear work/time mathematical model in elite cyclists (Bartram et al. 2017), with results suggesting that EP significantly overestimates CP (402 ± 33 W vs. 351 ± 21 W), and WEP underestimates $W'$ (15.5 ± 3.0 kJ vs. 24.3 ± 4.0 kJ). These results would suggest that the 3-min cycling test is not suitable for elite cyclists, with overtraining possible if using EP to set training sessions. These results are further supported by Bergstrom et al. (2014), who compared EP and WEP calculated from the 3-min cycling test to each of the five mathematical models used to calculate CP and $W'$. The results of their study suggested that EP significantly overestimated CP, and significantly underestimated $W'$ when calculated using each mathematical model. These results led the authors to raise some concerns about the validity of the 3-min cycling test to estimate CP and $W'$. 
The literature within this section has highlighted that some caution should be exercised if using the 3-min cycling test to estimate CP and \( W' \), with suggestions that the original protocol is sensitive to the testing ergometer, cadence selection, and participant fitness. Additionally, it is often reported that the 3-min cycling test provides an estimate for CP and \( W' \) from a single testing session, despite two testing sessions being required; the first being necessary to calculate GET and \( \dot{V}O_2\text{peak} \) (i.e. to calculate 50% \( \Delta \)), and this is often followed by a familiarisation session if the participants have little experience of the protocol. To overcome these concerns, recent research has focused on modifying the original 3-min cycling test protocol.

2.11 Modified All-Out Critical Power Protocols

With the aim of modifying the 3-min cycling test to become a truly single-day testing protocol, Bergstrom et al. (2012) suggested using a percentage of body mass (%BM) to set the fixed resistance used during the test. Rather than using the Lode Excalibur Sport ergometer, this study was carried out on a friction-braked cycle ergometer (818, Monark, Sweden), with the resistance set to 3.5% and 4.5%BM. The results suggested that EP was not significantly different to CP calculated from the linear work/time mathematical model for either 3.5%BM (173 W vs. 178 W) or 4.5%BM (186 W vs. 178 W). Furthermore, WEP was not significantly different to \( W' \) when calculated using 4.5%BM (9.8 kJ vs. 13.4 kJ), but was markedly lower than \( W' \) when using for 3.5%BM protocol (8.3 kJ vs. 13.4 kJ). Based on these results, the authors suggested that the 3-min cycling test could be completed against a resistance of 4.5%BM to estimate both CP and \( W' \) accurately, and that this protocol provided a suitable single-day alternative to the original 3-min cycling test protocol. A similar protocol was investigated by Clark, Murray and Pettitt (2013), although the selection of the %BM was based on the fitness of each participant (recreationally active = 3%BM, aerobic and anaerobic athletes = 4%BM, and endurance athletes = 5%BM). With comparable results to Bergstrom
et al. (2012), this study concluded that the EP and WEP calculated from %BM were not significantly different to EP and WEP calculated using the original 3-min cycling test (194 ± 40 W and 7.5 ± 2.1 kJ vs. 194 ± 39 W and 7.3 ± 3.0 kJ, respectively). An alternative testing protocol was also suggested by Dicks et al. (2016) who estimated 50% Δ from a self-reported physical activity rating, with no significant differences observed between EP and CP (235 ± 56 W vs. 230 ± 57 W) or between WEP and W’ (7.88 ± 2.91 kJ vs. 9.46 ± 4.15 kJ). The studies by Bergstrom et al. (2012), Clark, Murray and Pettitt (2013), and Dicks et al. (2016) suggest that alternative testing protocols could be used for the estimation of CP and W’ from a single testing session, without the need to calculate GET and VO2peak. Whilst the modified all-out testing protocols described above appear to provide valid estimations of CP and W’, each rely on calculating 50% Δ from estimates, or for the participants to self-select their current fitness level.

The 3-min cycling test is commonly completed on the Lode Excalibur Sport (Burnley, Doust and Vanhatalo 2006), or the SRM in isokinetic mode (Dekerle et al. 2014, Karsten et al. 2014a), with both ergometers typically limited to a laboratory environment due to their high cost. To overcome this issue, and to provide a more ecologically valid test, it was suggested that the 3-min cycling test could be completed using an athlete’s road bike and CompuTrainer indoor training ergometer (Clark et al. 2016). During their study, the participants were required to manually change gears, aiming to maintain the highest possible power output throughout the test. EP and WEP were compared to CP and W’ calculated from the linear work/time mathematical model (215 W vs. 212 W and 11.2 kJ vs. 12.1 kJ, respectively), and the linear power-1/time mathematical model (215 W vs. 213 W and 11.2 kJ vs. 11.7 kJ, respectively). The study by Clark et al. (2016) was the first to test the 3-min all-out protocol using a more accessible training system, with results suggesting that the CompuTrainer could be used to estimate CP and W’ from the 3-min cycling test; however,
some concerns were raised about the use of this protocol with all populations. The authors noted that novice cyclists are less likely to perform the test effectively due to the requirements of matching the required power output by manually changing gears and, therefore, this protocol/testing environment may be limited to highly-trained cyclists.

Finally, a study by Constantini, Sabapathy and Cross (2014) compared the original 3-min cycling testing protocol to a modified protocol that ensured that only one visit was required to estimate CP and \( W' \). This modified protocol combined an incremental ramp test to determine GET and \( \text{VO}_2\text{peak} \), with a 3-min cycling test, each separated by 20 min. The results found no significant differences for EP or WEP between the original 3-min cycling test (256 ± 118 W and 13.7 ± 4.5 kJ) and the combined testing protocol (254 ± 117 W and 13.7 ± 3.9 kJ).

One of the main concerns about this testing protocol is the requirement to complete two maximal testing sessions within 20 min, and despite this reducing the total number of testing sessions, the combined protocol would require a very high level of motivation, especially considering the 3-min cycling test on its own is extremely physiologically demanding.

The studies within this section suggest that the 3-min cycling test can be modified to remove the need for an initial testing session to calculate GET and \( \text{VO}_2\text{peak} \), and subsequently, the fixed resistance. It should be noted, however, that the above protocols did not directly compare EP and WEP to CP and \( W' \) calculated from the original CP model or complete a CP validation test. Based on these omissions, some assumptions must be made about the direct application and validity of these alternative testing protocols.

2.12 Power Measurement

There are several laboratory-based cycle ergometers that have been used in the calculation of CP and \( W' \) from the original or all-out testing protocols, for example, the Lode Excalibur.
Sport (Vanhatalo, Doust and Burnley 2008a, Ferguson et al. 2010, Bergstrom et al. 2014, Constantini, Sabapathy and Cross 2014, Black et al. 2015, Triska et al. 2015), SRM Ergometer (Dekerle et al. 2014, Karsten et al. 2014a), Velotron (Mattioni Maturana et al. 2016), CompuTrainer (Francis et al. 2010, McClave, LeBlanc and Hawkins 2011), Monark 814E (Brickley, Doust and Williams 2002), and Monark 818E (Bergstrom et al. 2012). With an increased popularity in cycle-mounted power measuring devices amongst cyclists of all levels, it is suggested that physiological testing protocols will continue to be modified to allow the determination of test results outside of a laboratory environment. The calculation of CP and $W'$ relies on an accurate measurement of both time and power output and, therefore, it is essential that the reliability and validity of the power measuring devices are tested prior to use. This section provides a review of the most commonly used laboratory- and field-based power meters, supporting the use of the power meters used within the experimental chapters of this thesis.

2.12.1 Laboratory-based Ergometers

The SRM Ergometer, which uses the SRM Powermeter, is known for its reliability and validity, and is often regarded as the “gold standard” in cycling (Hopker et al. 2010). In a study by Abbiss et al. (2009), the SRM demonstrated accuracy of <1% when compared to a dynamic calibration rig during constant-power tests at 250 W and 414 W. In a study by Gardner et al. (2004), 19 SRM Powermeters were assessed using a dynamic calibration rig, with results identifying that the most accurate SRM produced an error of between 0% (100 W) and –3% (800 W). Nonetheless, some concerns were raised about the variation between systems, and it was highlighted that the error at 100 W ranged from –10.4 to 1.0 W between systems. Following initial testing, the frequency vs. torque slope was adjusted to ensure that the SRM Powermeters were reading within ±2% of the dynamic calibration rig, and it was noted that this accuracy remained after 11 months of use. With the SRM Powermeter commonly accepted as the “gold standard” for measuring power output in cycling, the results of the
study by Gardner et al. (2004) highlight the importance of pre-test calibration, especially when trying to detect changes as low as 2%, which is common within cycling performance (Hopkins, Schabert and Hawley 2001). At 300 W, which is a power output commonly observed in elite cyclists, this would equate to an acceptable error of 5 W (Hopker et al. 2010).

The Lode Excalibur Sport is an electronically-braked ergometer commonly used within sports science research. It is often regarded as a “gold standard” in testing ergometry, with a CV of 0.7–1.5% for mean power output observed during TT performances (Driller 2012). The reliability of the Lode Excalibur Sport and CompuTrainer have also been investigated during an incremental testing protocol to exhaustion (Earnest et al. 2005). Earnest et al. (2005) found that the test-retest error for the Lode Excalibur Sport for TTE and peak power output was 1.0% and 1.5%, respectively. When comparing the Lode Excalibur Sport to the CompuTrainer, differences between TTE and peak power output were as high as 10% and 15%, respectively. The authors concluded that although the CompuTrainer provides a reliable measure of TTE and power output during an incremental ramp test, the results are not comparable to the Lode Excalibur Sport, and that care should be taken if transferring results between devices (e.g. testing vs. training). The Lode Excalibur Sport has received less attention with regards to its reliability and validity compared to the SRM Powermeter; however, it remains one of the most commonly used ergometers when investigating the reliability and validity of laboratory-based testing protocols (Jeukendrup et al. 1996, Reiser et al. 2000, Burnley, Doust and Vanhatalo 2006, Vanhatalo, Doust and Burnley 2007, Johnson et al. 2011, Wells et al. 2014, Hoefelmann et al. 2015, Morales-Alamo et al. 2015, Mitchell et al. 2018).
2.12.2 Field-based Power Meters

Laboratory-based ergometers are ideal for research and private consultancy; however, with a purchase price of more than £15,000, this often limits their use outside of sports science laboratories (Peiffer and Losco 2011). The development of the cycle-mounted power meter has provided athletes, coaches, and researchers with the opportunity to monitor performance (e.g. power output and cadence) using the athlete’s bicycle, rather than being restricted to a laboratory-based ergometer (Jones and Passfield 1998, Earnest et al. 2005, Bini, Hume and Cerviri 2011). Cycle-mounted power output measuring devices were initially developed in the late 1990s, with many affordable devices now available to amateur cyclists (Allen and Coggan 2012). The SRM Powermeter (crank) is regarded as the “gold standard” cycle-mounted power meter and is frequently used by professional cyclists (Passfield et al. 2016).

Over the last fifteen years, there has been a growth in cycle-mounted power meters with manufacturers continuing to develop cheaper alternatives to the SRM Powermeter. These include Stages (crank arm), PowerTap (hub) and ErgomoPro (bottom bracket) (Hopker and Jobson 2012). To ensure coaches and researchers have the confidence to use cycle-mounted power meters, extensive research has been carried out into the reliability and validity of these cheaper alternatives (Gardner et al. 2004, Bertucci et al. 2005, Kirkland et al. 2008, Sparks et al. 2015, Novak and Dascombe 2016). Bertucci et al. (2005) found a mean difference of –1.2% between the SRM Powermeter and the hub-based PowerTap when tested at 100–450 W. Additionally, they reported that the CV ranged from 0.7–2.1% (SRM) and 0.9–2.9% (PowerTap). The SRM Powermeter has also been compared to the ErgomoPro, which is a system fitted into the bottom bracket, with results reporting a CV of 1.4% (SRM) and 2.3% (ErgomoPro) during trials between 50 and 450 W (Kirkland et al. 2008). Significant differences were observed for the mean power output during all trials between the SRM and
ErgomoPro (233 ± 112 W vs. 228 ± 109 W, respectively), and it was suggested by the authors that these results could limit the use of this system in a research setting.

In 2010, Polar, in partnership with LOOK, brought to the market the first pedal-based power measurement system (LOOK Kéo power-pedal system). Not only were these pedal-based power meters easy to install, but they also offered the flexibility of being able to transfer between bikes without the need for specialist tools. Currently, two of the most common pedal-based power meters available are the PowerTap P1 (P1) and the Garmin Vector 2 (V2) pedals. Both sets of pedals include eight strain gauges housed within the pedal body to calculate torque directly at the pedal. Unlike some crank-based power meters, the P1 and V2 pedals allow torque to be measured for both legs, providing additional information to the athlete and coach (e.g. power balance between left and right leg). Until recently, however, pedal-based systems (e.g. LOOK Kéo) have not provided the same measure of reliability when compared to more traditional crank- or hub-based systems (Sparks et al. 2015). The results of the study by Sparks et al. (2015) raise some concerns about the use of pedal-based systems to detect the small test-retest differences which are likely to be observed during training or research (Sparks et al. 2015). Despite the LOOK Kéo pedals not demonstrating the same level of reliability as the SRM Powermeter, the authors suggested that these pedals offer a cheaper alternative to the SRM Powermeter and can provide useful power output data for a coach and athlete.

The use of pedal systems is supported by Bouillod et al. (2017) who reported that the Garmin Vector pedals (v1.0) provided reproducible data; however, some concerns were raised about the validity and sensitivity of these pedals when compared to the SRM Powermeter. These results were further supported by Novak and Dascombe (2016) who suggested that the Garmin Vector pedals (v1.0) overestimated power output by approximately 20 W, with a
technical error of estimate (TEE) of between 3.0 and 3.8% when compared to the SRM Powermeter. The authors suggested that the small differences in power output between the Garmin Vector pedals and the SRM Powermeter may be due to the different location that each device measures force. Power meters calculate power output using strain gauges which are housed within the body of the power meter, and are capable of providing a real-time power output to the cyclist via a cycling computer (Bini, Hume and Cerviri 2011). During cycling, the strain gauges’ electrical resistance will alter depending on the external force applied at the pedal, and together with an accurate calculation of cadence, power output can be calculated (Bini, Hume and Cerviri 2011). Due to the location of these strain gauges, it is reasonable to expect small differences between devices if they measure torque at different locations, with some dissipation in force occurring when not measuring directly at the foot (e.g. crank, hub or pedal). More recently, the P1 pedals were validated against a scientific SRM Powermeter at a range of power outputs (100–500 W) and cadences (70, 85 and 100 rev-min⁻¹) (Pallarés and Lillo-Bevia 2018). The results found that the P1 pedals slightly underestimated the SRM Powermeter by approximately 7 W; however, they provided a valid measure of power output across all tested conditions. The results from this study suggest that the P1 pedals offer reliable and valid data, and can be used as a cheaper alternative to laboratory-based ergometers for testing and training.

When completing experimental studies, it is essential to control for external variables, and it is known that temperature can affect the accuracy of power meters (Gardner et al. 2004). In a study comparing the effect of temperature on the accuracy of the SRM Powermeter and a PowerTap hub system, it was concluded that the power output between standard conditions (~21°C, ~40–55% relative humidity), and cold conditions (~6°C, ~60% relative humidity), could vary by as much as 5% (SRM) and 8% (PowerTap hub) (Gardner et al. 2004). It is possible to reduce this error by performing a zero-offset through the control unit, but it has
been suggested that it might take up to 15 min after exposure to a cooler environment for the power meter to stabilise. The results of the study by Gardner et al. (2004) highlight the importance of pre-test calibration and the testing environment, and where possible, all testing should be performed under controlled conditions. Current literature suggests that if regularly checked against a “gold standard” system, pedal-based power meters could be used to monitor the performance of well-trained cyclists (Bertucci et al. 2005). If these checks are not completed, it is possible that this may lead to over- or underestimation of power output, which could have a direct impact on training and performance (Bertucci et al. 2005, Novak and Dascombe 2016).

2.13 Summary

This review of literature introduced the CP concept and investigated several methodological issues that affect the calculation of CP and $W'$. It is generally agreed that CP demarcates the boundary between the heavy and severe exercise intensity domains, where a metabolic steady-state is observed; however, it has been suggested that CP is not frequently used by coaches or applied sports scientists due to the time-consuming protocol, and perceived mathematical complexity (Vanhatalo, Jones and Burnley 2011).

Over the last 10 years, research has focused on estimating CP and $W'$ from all-out testing protocols that can be completed in a single testing session. This review of literature has provided detail on the 3-min cycling test, and has highlighted some of the concerns about the original protocol, introduced by Burnley, Doust and Vanhatalo (2006). The 3-min cycling test is frequently used by contemporary researchers; however, the validity of this protocol for estimating CP and $W'$ has been questioned.
2.14 Research Questions and Aims

The overall aim of this thesis was to develop a novel all-out cycling testing protocol to provide reliable and valid estimates of CP and $W'$. A total of five experimental studies were completed to achieve the aims of the thesis:

**Study 1 – The reliability and validity of the 3-min cycling test in linear and isokinetic modes**

- **Summary:** The 3-min cycling test has received much attention over the last ten years; however, questions remain about the reliability and validity of this test when completed using different ergometer modes.
- **Aims:** To investigate the reliability and validity of the 3-min cycling test in estimating CP and $W'$ when performed against a fixed resistance (linear mode) and at a constant cadence (isokinetic mode).

**Study 2 – The 3-min cycling test is sensitive to changes in cadence using the Lode Excalibur Sport Ergometer**

- **Summary:** With the fixed resistance of the 3-min cycling test reliant upon the participant to self-select their preferred cadence, some concerns about this method were raised. Where the effect of cadence on the 3-min cycling test has previously been investigated, it was noted that these studies had not directly compared the participant's self-selected cadence to their ‘actual’ cadence observed from laboratory-based testing.
- **Aims:** To investigate the effect of cadence on the calculation of EP and WEP from the 3-min cycling test.
**Study 3 – Reliability and validity of the PowerTap P1 and Garmin Vector 2 pedals**

- **Summary:** With some limitations of the Lode Excalibur Sport’s software to export data, it was suggested that a cycle-mounted power pedals could be used in the final study of this thesis.

- **Aims:** The first aim was to investigate the reliability of two commonly used power pedals; the PowerTap P1 and Garmin Vector 2 pedals. The second aim was to evaluate agreement between the PowerTap P1 and Garmin Vector 2 pedals with the Lode Excalibur Sport.

**Study 4 – The reliability and validity of the PowerTap P1 pedals before and after 100 hours of use**

- **Summary:** Reliability and validity studies on sports science testing equipment is rarely completed over an extended period and, therefore, it was suggested that the reliability and validity of the P1 pedals should be tested before and after extensive laboratory use.

- **Aims:** To compare the reliability and validity of the P1 pedals before and after approximately 100 h of laboratory use.

**Study 5 – A novel all-out cycling protocol to estimate critical power and the finite work capacity**

- **Summary:** It was suggested that a novel all-out cycling test could address some of the potential limitations of the 3-min cycling test raised in studies one and two.

- **Aims:** The first aim was to investigate the reliability and validity of a novel all-out cycling test to estimate CP and $W'$. The second aim was to investigate the physiological responses to cycling at CP calculated from the original CP protocol, the 3-min cycling test protocol, and a novel all-out cycling test protocol.
Figure 2.14 Research journey. The red lines represent the direction that has been followed.
3 GENERAL METHODS

This thesis consists of five experimental research studies focussing on the CP concept within cycling. This chapter outlines the general methods used throughout this period of doctoral study, with the specific details found within the relevant experimental chapters.

3.1 Ethics Considerations

Before the start of each study, ethics approval was gained from the Health, Exercise and Sport Science ethics committee at Solent University, with all data collection completed in accordance with the Declaration of Helsinki (2013). The author of this thesis was a BASES Accredited Sport and Exercise Science throughout this research and ensured that all testing sessions adhered to the BASES Code of Conduct (2016). Throughout testing, the associated risks were mitigated through appropriate risk assessments and safety checks on equipment. During each testing session, a trained first aider was present, with access to both oxygen and a defibrillator. Finally, all data collection was completed in a BASES accredited laboratory, ensuring that the highest level of professionalism and quality assurance were maintained.

3.2 Participants

For each study within this thesis, participants were recruited through a convenience sampling method with a call of interest sent to local cycling clubs and posted on social media sites (e.g. Twitter and Facebook). Participants who volunteered to take part in each study trained at least 4 days per week and were accustomed to high-intensity exercise during their day-to-day training. The training status of each participant was verbally confirmed at the beginning of each study. Participants were not paid to take part in any of the studies, but a detailed report of their results was provided upon completion. Only male participants were used within this thesis to avoid any unknown confounding effects of sex differences on the
calculation of CP and $W'$. Before each testing session, the participants were instructed to avoid heavy exercise for 24 h and food intake for 2 h (Shearman et al. 2016). Participants were also instructed to drink 500 ml of water 2 h prior to testing (Keir et al. 2015).

3.3 Participant Screening and Care

Before each testing session, participants completed a physical activity readiness questionnaire (PAR-Q) and an informed consent form (Appendix C). Resting blood pressure (M2, Omron, Japan) was taken prior to each testing session to ensure that the participant's blood pressure was within the laboratory guidelines (90/60–140/90 mmHg). Additionally, a 12-lead electrocardiogram (CardioExpress SL12, Seca, Germany) was also carried out prior to studies one, two and five to ensure that the participants did not show any sign of cardiac arrhythmias (Figure 3.1).

![Figure 3.1 Lead wire and electrode placement during 12-lead electrocardiogram (CardioExpress SL 12 Reference Guide).](image)

Following the completion of each testing session, participants were asked to complete a 10-min active warm down (~50 W), with participants monitored for a further 15 min before being allowed to leave the laboratory.
3.4 Ergometer Set-up

3.4.1 Ergometer Position

All testing sessions were carried out using an electronically-braked cycle ergometer (Excalibur Sport, Lode, The Netherlands). To standardise testing sessions, the participant’s self-selected ergometer measurements were noted during their first testing session and used for all subsequent sessions. The Lode Excalibur Sport allows the following measures to be digitally recorded (Figure 3.2):

- Saddle height, angle and horizontal position.
- Handlebar height and horizontal position.

![Figure 3.2 Lode Excalibur Sport dimensions and adjustment (Lode Excalibur Sport User Guide).](image)

3.4.2 Standard Pedals

For studies one and two, the participants used their own pedals and shoes during all testing sessions. These included Shimano SPD, Shimano SPD-SL, LOOK Kéo, and Speedplay. The pedals were installed following the manufacturer’s guidelines and recommended torque settings.
3.4.3 Pedal-based Power Meters

During study three, the V2 (Vector 2, Garmin, USA) and P1 (P1, PowerTap, USA) pedal-based power meters were used to record power output and cadence. During studies four and five, power output and cadence were recorded using the P1 pedal-based power meter only.

Prior to each testing session, the pedals were installed to a torque of 40 Nm following the manufacturer’s guidelines (TW-2, Park Tool, USA). Unlike the P1 pedals, the V2 pedals use a pedal pod to house the battery and transmit raw data to a compatible bike computer (Edge 810, Garmin, Switzerland). In line with the manufacturer’s recommendations, the pedal pod was placed on the leading edge of the crank and facing downwards when the pedals were in a forward-facing position (Figure 3.3).

![Garmin Vector 2 pedal pod orientation](image)

**Figure 3.3** Garmin Vector 2 pedal pod orientation.

3.5 Calibration

3.5.1 Metabolic Cart

During studies one, two and five, a metabolic cart was used to measure and export raw data for minute ventilation (\(\dot{V}_E\)), VO\(_2\), carbon dioxide production (VCO\(_2\)) and respiratory exchange ratio (RER) (study one: Oxycon Pro, Jaeger, Germany; studies two and five: Masterscreen CPX, Viasys, Germany). Before the start of each study, the metabolic carts were serviced by Vyaire Medical Inc., with a manual calibration process occurring immediately before each testing session:
- Ambient conditions: The system automatically measures temperature and barometric pressure, with relative humidity entered manually from a hygrometer reading (Fischer, Haar-Hygrometer, Germany).

- Volume: The volume transducer and sample line were connected to a factory calibrated syringe (5 L syringe, Viasys, Germany). The system required six consistent strokes to be performed, with the calibration automatically saved if these strokes were deemed ‘successful’ by the system.

- Gas: A two-point gas calibration was carried out using a known gas mix of approximately 16% O₂ and 5% CO₂ and ensuring that the pressure was set to 1.5–2.0 bar. Prior to calibration, the specific fractions of O₂ and CO₂ were entered into the system from the certificate provided when the gas mixture was purchased (BOC, UK).

3.5.2 Blood Analyser

Blood lactate was analysed from fingertip capillary blood samples using a portable analyser (Lactate Pro, Arkray, UK) for study one, and a desktop analyser (Biosen C-Line, EKF Diagnostics, Germany) for studies two and five.

3.5.2.1 Lactate Pro

The Lactate Pro cannot be calibrated manually; however, a check strip was used prior to each test to ensure that the analyser was measuring within the manufacturer’s acceptable range (2.1–2.6 mmol·L⁻¹). Additionally, Lactate Pro strips are coded, and care was taken to ensure that the correct code was used prior to each testing session.

3.5.2.2 Biosen C-Line

The Biosen C-Line desktop analyser was set to automatically calibrate every 60 min using the periodic calibration mode, and a multi-standard solution of 12 mmol·L⁻¹ taken from 2 mL micro test tubes. Throughout this research, the sports science laboratory technicians at
Solent University carried out a monthly linearity check on the Biosen C-Line analyser using known samples of 2, 7 and 18 mmol·L⁻¹. This system was also serviced on a bi-annual basis by the laboratory technicians using a service box purchased from EKF Diagnostics.

3.5.3 Lode Excalibur Sport

The Lode Excalibur Sport does not require manual calibration before use; however, annual servicing was carried out by Cranlea Human Performance Ltd prior to each study, which included calibration using a dynamic calibration rig (Portable Calibrator 2000, Lode, The Netherlands). During each service, the ergometer was calibrated at 25, 50, 100 and 150 W (60 rev·min⁻¹), and at 200, 300, 400 and 500 W (100 rev·min⁻¹), with an average error of 1.2% for power output and 0.1% for cadence, when compared to the dynamic calibration rig.

3.5.4 Garmin Vector 2 and PowerTap P1 pedals

The V2 and P1 pedals were both factory calibrated, and it is not possible to manually calibrate them after they are purchased. To maintain accuracy, it is essential to ensure that they were set up correctly prior to use by following the manufacturer’s guidelines. This included setting the pedal angles and completing the zero-offset procedure prior to all testing sessions. The zero-offset procedure measures the strain gauges when no torque is being applied to the pedals and is completed to adjust for external factors such as temperature and humidity, which are known to affect the accuracy of power measuring devices that use strain gauges (Gardner et al. 2004).

3.6 Procedures

3.6.1 GET, MAP and \( \dot{\text{VO}}_{2\text{peak}} \) Protocols

An incremental ramp test was carried out for studies one, two and five to calculate GET, MAP and \( \dot{\text{VO}}_{2\text{peak}} \) for each participant, and was completed using the Lode Excalibur Sport’s hyperbolic mode. The warm up for each incremental ramp test was standardised to 10 min
cycling at 100 W. The test started at a power output of 150 W, with increments of 5 W occurring every 15 s (20 W·min⁻¹) (Davis et al. 1982). Participants were instructed to cycle until volitional exhaustion, and the test was terminated when cadence dropped by more than 10 rev·min⁻¹ below the participant’s preferred cadence for more than 5 s. GET was calculated using the V-slope method described by Beaver, Waseserman and Whipp (1986), and outlined in (Figure 3.4). MAP was determined as the highest 30-s mean power output calculated from the raw exported data (Karsten et al. 2014a), with \( \dot{V}O_2 \)peak determined as the highest 30-s average in \( \dot{V}O_2 \) calculated from 5-s average exported data (Robergs, Dwyer and Astorino 2010).

![Figure 3.4](image-url) An example plot of pulmonary gas data to determine GET from \( \dot{V}O_2 \) vs. \( \dot{V}CO_2 \) taken during an incremental cycling test. The arrow identifies GET.

### 3.6.2 Original Critical Power Protocol

CP and \( W' \) were calculated from three TTE tests at 80, 100 and 105% MAP (Karsten et al. 2014a) using the Lode Excalibur Sport’s hyperbolic mode. Prior to each TTE test, participants completed a standardised warm-up of 10 min cycling at 100 W. Throughout each testing
session, participants were instructed to cycle at their preferred cadence until volitional exhaustion. Tests were terminated, and the time-to-exhaustion noted, once cadence dropped by more than 10 rev·min\(^{-1}\) below the pre-determined preferred cadence for more than 5 s. Consistent with previous literature (Vanhatalo, Doust and Burnley 2007, Karsten et al. 2014a), CP and \(W'\) were calculated using the following linear 2-parameter mathematical model:

\[
P = W'\left(\frac{1}{t}\right) + CP \quad \text{(equation 3)}
\]

Using the above mathematical model, CP was calculated as the \(y\)-intercept, with \(W'\) calculated as the slope of the linear relationship between power output and the inverse of time (refer to section 2.4.1).

3.6.3 The 3-min Cycling Tests

During this thesis, the 3-min cycling test was performed against a fixed resistance (linear mode), and at a fixed cadence (isokinetic mode), using the Lode Excalibur Sport. The fixed resistance was set in the ergometer’s linear mode using the following equation:

\[
\text{linear factor (resistance)} = \frac{50\% \Delta}{\text{preferred cadence}^2} \quad \text{(equation 7)}
\]

In line with the research by Vanhatalo, Doust and Burnley (2007), 50\% \(\Delta\) was determined as 50\% of the difference between GET and \(\dot{V}O_{2\text{peak}}\), with cadence self-selected by each participant for studies one and two. During study five, the preferred cadence was selected as the mean cadence observed during the incremental ramp test protocol. During the isokinetic testing sessions, participants cycled at their preferred cadence for the duration of
each trial (Karsten et al. 2014a). In this mode, the participants were unable to cycle faster than the selected cadence, and an increase in torque, resulted in an increased resistance.

For each of the 3-min cycling tests, EP was calculated as the mean power output observed over the final 30 s of the test, with WEP calculated as the power-time integral above EP (Figure 2.11). The power-time integral was calculated using the following equation:

\[ \int_{a}^{b} f(x) \, dx = \frac{b-a}{n} \left[ (y_0 + y_n) + 2(y_1 + y_2 + y_3 + \cdots) \right] \]  

(equation 8)

Breath-by-breath analysis and heart rate were measured for all tests to ensure that the participants attained the testing criteria defined by Jones et al. (2010).

3.6.4 Blood Analysis

Before sampling, the puncture site was cleansed thoroughly using an alcoholic wipe (70% Isopropyl alcohol solution) and then left to air dry. A single-use lancet (Safe-T-Pro, Accu-Chek, UK) was used to puncture the skin across the fingerprint, and the first drop of blood was wiped away with a tissue to ensure that the sample was not contaminated with sweat. Care was taken during each sample to ensure that the finger was not squeezed too hard as this could dilute the sample with plasma, and increase the chances of haemolysis (WHO, 2010). A small sample of blood was obtained (5 µL for the Lactate Pro and 20 µL for the Biosen C-Line) ensuring that no air bubbles were present in the testing strip (Lactate Pro) or capillary tube (Biosen C-Line).

3.7 Statistical Analyses

An experimental research design was adopted for each study within this thesis allowing individual hypotheses to be tested through quantitative statistical analyses. Throughout this
thesis, descriptive statistics were expressed as means ± SD, with all statistical analyses performed using SPSS (version 23.0, IBM Corp, USA) and GraphPad (version 7.0, Prism, USA).

During each experimental study, data were assessed for normality using the Shapiro-Wilk test prior to analysis. For each study, agreement between variables was assessed using limits of agreement (LoA) (Bland and Altman 1986). Effect sizes (ES) were calculated using Cohen’s $d$; trivial (<0.19), small (0.20–0.49), medium (0.50–0.79) and large (>0.80) (Cumming 2014), and relationships were measured using Pearson’s product moment correlation coefficient. For each study, test-retest reliability was measured using CV and ICC. A detailed description of the statistical tests used in each study can be found within the relevant experimental chapters.

### 3.7.1 Power Analysis

An *a priori* power analysis was performed using G*Power (version 3.1.9.2, Franz Faul, Germany) before each study to establish the number of participants (n) required to meet appropriate power (Table 3.1). The number of participants initially recruited was increased by 10% to account for potential loss (e.g. injury) in line with guidelines presented by Batterham and Atkinson (2005).

**Table 3.1** Power Analysis carried out in G*Power to determine the number of participants required in each experimental study.

<table>
<thead>
<tr>
<th>Study</th>
<th>Reference</th>
<th>Group 1 Mean (W)</th>
<th>Group 2 Mean (W)</th>
<th>Group 1 SD (W)</th>
<th>Group 2 SD (W)</th>
<th>Effect Size</th>
<th>Alpha</th>
<th>Power</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+2</td>
<td>Karsten <em>et al.</em> (2014a)</td>
<td>290</td>
<td>253</td>
<td>41</td>
<td>41</td>
<td>0.90</td>
<td>0.05</td>
<td>0.80</td>
<td>12</td>
</tr>
<tr>
<td>3+4</td>
<td>Bini <em>et al.</em> (2011)</td>
<td>343</td>
<td>265</td>
<td>73</td>
<td>27</td>
<td>1.22</td>
<td>0.05</td>
<td>0.80</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>Wright <em>et al.</em> (2017)</td>
<td>240</td>
<td>275</td>
<td>23</td>
<td>41</td>
<td>0.98</td>
<td>0.05</td>
<td>0.80</td>
<td>10</td>
</tr>
</tbody>
</table>
4 STUDY ONE: THE RELIABILITY AND VALIDITY OF THE 3-MIN CYCLING TEST IN LINEAR AND ISOKINETIC MODES

4.1 Introduction

Aspects of this chapter have been published in the International Journal of Sports Medicine (Wright, Bruce-Low and Jobson 2017). As discussed in chapter 2, the time-consuming nature of the original CP testing protocol has led researchers to focus on single-day protocols for the estimation of CP and \( W' \) (Vanhatalo, Doust and Burnley 2007). The practical benefits of a single-session testing protocol to estimate the parameters of the power-duration relationship have led to several studies investigating the reliability and validity of the 3-min cycling test using a variety of cycle ergometers and testing modes (Vanhatalo, Doust and Burnley 2007, McClave, LeBlanc and Hawkins 2011, Bergstrom et al. 2012, Karsten et al. 2014a).

It has been suggested that the 3-min cycling test, performed against a fixed resistance using the Lode Excalibur Sport, provides near identical estimates of CP (287 ± 55 W vs. 287 ± 56 W), and very similar estimates of \( W' \) (15.0 ± 4.7 kJ vs. 15.4 ± 3.5 kJ) (Vanhatalo, Doust and Burnley 2007); however, research is less clear when using isokinetic ergometry (Dekerle et al. 2014, Karsten et al. 2014a, Tsai 2015). Due to the physiological basis of the 3-min cycling test, it was argued that the mode of measurement should not affect the estimation of either CP or \( W' \) (Karsten et al. 2014a), and to test this hypothesis, the authors completed the 3-min cycling test using the SRM ergometer set in isokinetic mode. The results suggested that, while providing a reliable estimate of EP, the 3-min cycling test performed in isokinetic mode results in a significantly higher estimate of CP (290 ± 41 W vs. 259 ± 38 W) and a significantly lower estimate of \( W' \) (12.5 ± 4.3 kJ vs. 16.6 ± 4.8 kJ) when compared to the original CP test protocol. In a similar study, Dekerle et al. (2014) reported no significant difference between
CP and EP when the 3-min cycling test was performed in isokinetic mode at 60 and 100 rev·min\(^{-1}\), but with low levels of agreement, some concerns were raised about using the 3-min cycling test to estimate CP. In contrast, Tsai (2015) reported that the 3-min cycling test underestimated CP by approximately 4% when performed in isokinetic mode.

Using a repeated-measures study design, the first experimental study in this thesis aimed to investigate the reliability and concurrent validity of the 3-min cycling test in estimating CP and \(W'\) when performed against a fixed resistance (linear mode) and at a constant cadence (isokinetic mode). It was hypothesised that 1) the linear mode would provide a reliable and valid estimate of CP, 2) the linear mode would provide a reliable and valid estimate of \(W'\), 3) the isokinetic mode would provide a reliable and valid estimate of CP, and 4) the isokinetic mode would provide a reliable and valid estimate of \(W'\).

4.2 Methods
4.2.1 Participants

Twelve male cyclists (mean ± SD: age 32 ± 7 years, body mass 81.6 ± 8.6 kg, MAP 349 ± 36 W, \(\text{VO}_{2\text{peak}}\) 4.4 ± 0.5 L·min\(^{-1}\)) completed a PAR-Q and provided written informed consent to participate in the study. Each participant took part in eight tests, each separated by a minimum of 48 h. The first testing session was carried out to calculate GET, MAP and \(\text{VO}_{2\text{peak}}\) along with providing each participant with a familiarisation of the 3-min cycling tests. The remaining testing sessions were completed to calculate CP and \(W'\), and the estimates EP and WEP, using the original and 3-min cycling test protocols, respectively. All testing was completed using an electronically-braked cycle ergometer (Excalibur Sport, Lode, The Netherlands). Following the measurement of GET, MAP and \(\text{VO}_{2\text{peak}}\), subsequent tests were carried out in a randomised order. During all testing sessions, strong verbal encouragement was provided, but no feedback was given regarding elapsed time or power output.
4.2.2 GET, MAP and $\dot{V}O_{2\text{peak}}$ Protocols

Participants completed an incremental exhaustive ramp test (20 W·min$^{-1}$) to volitional exhaustion to determine GET, MAP and $\dot{V}O_{2\text{peak}}$. Breath-by-breath expired air (Oxycon Pro, Jaeger, Germany) and heart rate (RCX5, Polar, Finland) were recorded at 5-s intervals with a post-test capillary blood lactate sample (Lactate Pro, Arkray, UK) taken immediately after completion of each test.

4.2.3 Original Critical Power Test

On separate days, each participant completed three tests to exhaustion at 80, 100 and 105% MAP (Karsten et al. 2014a). During each test, the participants were instructed to cycle at their preferred cadence until volitional exhaustion with tests terminated once cadence dropped by more than 10 rev·min$^{-1}$ below the pre-determined preferred cadence for more than 5 s. Consistent with Vanhatalo, Doust and Burnley (2007) and Karsten et al. (2014a), CP and $W'$ were calculated from the linear power-1/time mathematical model (Whipp et al. 1982).

4.2.4 3-min Cycling Tests

On different days, four tests were carried out to calculate EP and WEP from two separate 3-min protocols. Two tests were carried out against a fixed resistance (i.e. linear mode) and two using a fixed cadence (i.e. isokinetic mode). Following a 10-min warm up at 100 W, all 3-min cycling tests started with a 30-s period of unloaded cycling at the participant’s preferred cadence. During the final 10 s of this period the participants were instructed to increase their cadence to approximately 100–110 rev·min$^{-1}$ and, after a countdown, were encouraged to attain peak power output in the first 5 s of the 3-min cycling tests. During the linear tests, this was achieved by encouraging the participants to cycle at the highest possible cadence throughout the test, and it was clearly explained that the test should not be paced. During the isokinetic tests, the participants were encouraged to cycle at maximal effort throughout
each test. For each of the 3-min cycling tests, EP was calculated as the mean power output over the final 30 s with WEP calculated as the power-time integral above EP.

4.2.5 Statistical Analyses

All data were normally distributed as assessed by Shapiro-Wilk tests of normality ($P > 0.05$). Consistent with Karsten et al. (2014a) and Vanhatalo, Doust and Burnley (2007), comparisons between CP and EP, and between $W'$ and WEP for both the linear and isokinetic tests were analysed using a one-way repeated-measures ANOVA and LoA (Bland and Altman 1986). ES were also calculated using Cohen’s $d$; trivial (<0.19), small (0.20–0.49), medium (0.50–0.79) and large (>0.80) (Cumming 2014). In addition, Pearson’s product moment correlation coefficients were carried out to measure relationships between CP and EP, and between $W'$ and WEP. The reliability between testing sessions was measured using CV and ICC, and consistent with Karsten et al. (2014a), the error associated with predicting EP and WEP from linear regression methods was measured using standard error of estimates (SEE). Statistical significance was accepted at $P < 0.05$ with all data reported as mean ± SD.

4.3 Results

The mean $\dot{V}_\text{O}_\text{2,peak}$ and peak blood lactate for each testing protocol can be found in Table 4.1. CP and $W'$ calculated from the linear power-1/time mathematical model resulted in an $R^2$ value of 0.97 ± 0.03. The time-to-exhaustion for each constant work rate test used to calculate CP and $W'$ was 179 ± 29 s (105% MAP), 236 ± 39 s (100% MAP) and 679 ± 209 s (80% MAP) (Table 4.2). Table 4.2 also highlights the mean $\dot{V}_\text{O}_\text{2,peak}$ observed during each testing protocol, with 95% ramp test $\dot{V}_\text{O}_\text{2,peak}$ observed for all TTE conditions.
Table 4.1 Mean values (± SD) for \( \text{VO}_{\text{peak}} \), peak blood lactate, CP and \( W' \) observed during each testing session.

<table>
<thead>
<tr>
<th>Testing session</th>
<th>( \text{VO}_{\text{peak}} ) (L·min(^{-1}))</th>
<th>Peak blood lactate (mmol·L(^{-1}))</th>
<th>CP/EP (W)</th>
<th>( W'/WEP ) (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp protocol</td>
<td>4.4 ± 0.5</td>
<td>11.3 ± 0.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Original CP protocol</td>
<td>4.3 ± 0.5</td>
<td>11.5 ± 2.1</td>
<td>245 ± 26</td>
<td>22.7 ± 5.6</td>
</tr>
<tr>
<td>3-min cycling test (isokinetic)</td>
<td>4.5 ± 0.5</td>
<td>12.5 ± 2.3</td>
<td>241 ± 23</td>
<td>15.6 ± 5.6*</td>
</tr>
<tr>
<td>3-min cycling test (linear)</td>
<td>4.4 ± 0.4</td>
<td>12.8 ± 2.1</td>
<td>275 ± 41*</td>
<td>13.5 ± 4.7*</td>
</tr>
</tbody>
</table>

\* Significantly different from the original CP protocol (\( P < 0.005 \))

Table 4.2 Mean values (±SD) for oxygen uptake and time-to-exhaustion observed during each testing session.

<table>
<thead>
<tr>
<th>Testing session</th>
<th>( \text{VO}_{\text{peak}} ) (L·min(^{-1}))</th>
<th>TTE (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{VO}_{\text{peak}} ) ramp test</td>
<td>4.4 ± 0.5</td>
<td>675 ± 87</td>
</tr>
<tr>
<td>80% MAP</td>
<td>4.3 ± 0.5</td>
<td>679 ± 209</td>
</tr>
<tr>
<td>100% MAP</td>
<td>4.4 ± 0.5</td>
<td>236 ± 39</td>
</tr>
<tr>
<td>105% MAP</td>
<td>4.2 ± 0.5</td>
<td>179 ± 29</td>
</tr>
</tbody>
</table>

A one-way repeated-measures ANOVA showed no significant differences between EP-isokinetic and CP (241 ± 23 W vs. 245 ± 26 W, \( P = 1.000 \), 95% LoA of -4 ± 30 W, ES = 0.16).

There were significant differences between EP-linear and CP (275 ± 41 W vs. 245 ± 26 W, \( P = 0.005 \), 95% LoA of 30 ± 47 W, ES = 0.84). The LoA between CP and the EP estimates from the isokinetic and linear tests are shown in Figure 4.1.

Figure 4.1 Bland-Altman plots showing the limits of agreement between (a) EP-isokinetic and CP, and (b) EP-linear and CP. The solid line represents the mean difference in power output, and the dashed line represents the 95% limits of agreement.
Significant differences were identified between WEP-isokinetic and \( W' \) (15.6 ± 5.6 kJ vs. 22.7 ± 5.6 kJ, \( P < 0.001 \), 95% LoA of −7.1 ± 9.5 kJ, ES = 1.27), and between WEP-linear and \( W' \) (13.5 ± 4.7 kJ vs. 22.7 ± 5.6 kJ, \( P < 0.001 \), 95% LoA of −9.3 ± 9.0 kJ, ES = 1.77). The LoA between WEP-isokinetic and \( W' \), and between WEP-isokinetic and \( W' \) are illustrated in Figure 4.2.

![Figure 4.2](image)

Figure 4.2 Bland-Altman plots showing the limits of agreement between (a) WEP-isokinetic and \( W' \), and (b) WEP-linear and \( W' \). The solid line represents the mean difference in power output, and the dashed line represents the 95% limits of agreement.

The SEE and Pearson’s product moment correlation coefficients between EP-isokinetic and CP, EP-linear and CP, WEP-isokinetic and \( W' \) and WEP-linear and \( W' \) are shown in Table 4.3 and Figure 4.3.

<table>
<thead>
<tr>
<th></th>
<th>Isokinetic</th>
<th>Linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>SEE</td>
<td>SEE%</td>
</tr>
<tr>
<td>EP vs. CP</td>
<td>0.82, ( P = 0.001 )</td>
<td>13 W</td>
</tr>
<tr>
<td>WEP vs. ( W' )</td>
<td>0.63, ( P = 0.029 )</td>
<td>4.2 kJ</td>
</tr>
</tbody>
</table>
The CV for EP-isokinetic, EP-linear, WEP-isokinetic and WEP-linear was 1.9%, 1.2%, 8.4% and 5.4%, respectively, between tests 1 and 2. The ICC for EP-isokinetic was 0.97 (95% CI = 0.91–0.99), \( P < 0.001 \), EP-linear was 0.99 (95% CI = 0.98–0.99), \( P < 0.001 \), WEP-isokinetic was 0.94 (95% CI = 0.80–0.98), \( P < 0.001 \), and WEP-linear was 0.98 (95% CI = 0.93–0.99), \( P < 0.001 \) (Table 4.4).

**Table 4.4** Coefficient of variation and intraclass correlation coefficients between testing sessions for EP-isokinetic, EP-linear, WEP-isokinetic and WEP-linear.

<table>
<thead>
<tr>
<th>Testing Session</th>
<th>CV (%)</th>
<th>ICC (α)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP-isokinetic (1 vs. 2)</td>
<td>1.9</td>
<td>0.97</td>
</tr>
<tr>
<td>EP-linear (1 vs. 2)</td>
<td>1.2</td>
<td>0.99</td>
</tr>
<tr>
<td>WEP-isokinetic (1 vs. 2)</td>
<td>8.4</td>
<td>0.94</td>
</tr>
<tr>
<td>WEP-linear (1 vs. 2)</td>
<td>5.4</td>
<td>0.98</td>
</tr>
</tbody>
</table>
4.4 Discussion

The low CV and high ICC (Table 4.4) indicate that the 3-min cycling test in isokinetic mode provides a reliable measure of EP. With the mean EP within 5 W of CP calculated from the original CP test, the results also suggest that the isokinetic mode provides a valid estimation of the CP measurement. When performed against a fixed resistance (i.e. linear mode) the 3-min cycling test provides a reliable measure of EP; however, with EP significantly overestimating CP by approximately 30 W, questions are raised about the validity of the testing protocol when completed in this mode (Figure 4.4). Additionally, results suggest that neither 3-min cycling test mode provides a reliable measure of WEP, or a valid estimate of $W'$, with both testing modes significantly underestimating $W'$. The hypotheses that the linear mode would provide a reliable and valid estimate of CP and $W'$ have both been rejected. The hypothesis that the isokinetic mode would provide a reliable and valid estimate of CP has been accepted. Finally, the hypothesis that the isokinetic mode would provide a reliable and valid estimate of $W'$ has been rejected.
Karsten et al. (2014a) found that whilst providing a reliable measure of EP, the 3-min all-out test carried out in the isokinetic mode overestimated CP by approximately 37 W when compared to the linear power-1/time mathematical model. In a similar study Dekerle et al. (2014), found that there was no significant difference between EP and CP when the 3-min cycling test was carried out at 60 and 100 rev-min\(^{-1}\), and in contrast, Tsai (2015) found that EP underestimated CP by approximately 11 W when carried out in isokinetic mode. The results from the present study contrast with both Karsten et al. (2014a) and Tsai (2015) with no significant difference observed between EP-isokinetic and CP (241 ± 23 W vs. 245 ± 26 W).

It is possible that the differences observed in the studies above may be due to the small differences in protocol used to calculate CP and \(W'\). Karsten et al. (2014a) used 3 TTE tests at 80, 100 and 105% MAP with the aim of each test lasting 2–15 min. The linear 1/time mathematical model resulted in a very good fit (\(R^2 = 0.99 ± 0.001\)); however, it should be highlighted that the duration of each TTE was not reported, and it is possible that some participants reached exhaustion in less than 2 min for the 105% MAP test and longer than 15 min for the 80% MAP test. To reduce the error when calculating CP and \(W'\), Dekerle et al. (2014) initially completed 3 TTE tests, with an additional test included if the error was >5 W. In their study, it was suggested that the TTE tests would elicit exhaustion within 3–15 min; however, as with the study by Karsten et al. (2014a), these data were not included. Finally, Tsai (2015) completed 4 TTE tests to calculate CP and \(W'\), which were shorter than those used by Karsten et al. (2014a) and Dekerle et al. (2014), with exhaustion occurring between 1–10 min. It has previously been suggested that shorter duration TTE tests are likely to result in an overestimation of CP and an underestimation of \(W'\) (Bishop, Jenkins and Howard 1998, Mattioni Maturana et al. 2018), potentially explaining why Tsai (2015) found EP to underestimate CP.
The results from the present study also contradict the original research completed using a fixed resistance (Vanhatalo, Doust and Burnley 2007). Vanhatalo, Doust and Burnley (2007) reported near-identical values for EP and CP, whereas the present study observed significant differences between EP-linear and CP (275 ± 41 W vs. 245 ± 26 W, P = 0.004). Despite the results suggesting that the 3-min cycling test in isokinetic mode provides a very close estimate of CP, some questions are raised regarding the validity of the 3-min cycling test when carried out against a fixed resistance following the protocol described by Vanhatalo, Doust and Burnley (2007).

For both testing modes, it would appear that the reliability of EP calculated from the 3-min cycling test is good, and in line with previous research (Johnson et al. 2011, Karsten et al. 2014a). The reliability of EP-isokinetic and EP-linear between testing sessions was highlighted with a CV of 1.9% and 1.2%, respectively, which is less than the acceptable 5% limit suggested by Hopkins (2000a). The reliability of EP is further confirmed with an ICC for EP-isokinetic and EP-linear of 0.97 and 0.99, respectively. Despite WEP-isokinetic and WEP-linear resulting in an ICC of 0.94 and 0.98, respectively between testing session, the results of the present study highlight some concerns about the reliability of this parameter with a CV of 8.4% and 5.4%, respectively, observed (Table 4.4).

Data collection during the present study differed to Karsten et al. (2014a) only with the additional measurement of pulmonary gases during all tests. During all testing sessions of the present study, participants met the criteria for a successful test as stipulated by Jones et al. (2010). On only a single occasion was a participant required to repeat one of the testing sessions, this the result of a decremental trend in VO₂ during the final 30 s of one of the 3-min cycling tests. Without the measurement of pulmonary gases, Karsten et al. (2014a) were
unable to state with certainty if the criteria defined by Jones et al. (2010) were met during all testing sessions and it could be suggested that the participants in their study may not have exercised at a sufficiently high intensity throughout each test. The physical demands of participating in this study were high, with eight exhaustive testing sessions carried out by each participant. A randomised trial order was carried out to reduce the likelihood of any changes in fitness affecting the results; however, it should be acknowledged as a potential limitation and a factor which may have affected the calculation of both CP and $W'$. Another limitation of this study was the lack of a CP validation test following the calculation of CP as suggested by Clark, Murray and Pettitt (2013).

A key result of this study was the significant overestimation of EP when the 3-min cycling test was carried out against a fixed resistance, especially when compared to the original research by Vanhatalo, Doust and Burnley (2007) who found EP and CP to be almost identical. It is plausible to explain these differences by the cadence selected to calculate the linear factor for each participant, with previous research suggesting that EP is sensitive to small changes in cadence (Vanhatalo, Doust and Burnley 2008a). Prior to completing the 3-min cycling test using the protocol described by Vanhatalo, Doust and Burnley (2007), the fixed resistance (i.e. linear factor) needs to be calculated. This is achieved by asking each participant for their preferred cadence, and it was noted that several participants stated a range between 5–10 rev·min$^{-1}$, for example, 90–95 rev·min$^{-1}$. This given range in cadence could help to explain why differences are noted within the literature in both testing modes and it is possible that the cadences selected for some participants were too low.

Trained cyclists typically state that their preferred cadence is between 90–100 rev·min$^{-1}$, but this will depend on the demands of the ride, for example during a TT or mountain stage (Abbiss, Peiffer and Laursen 2009). A study by Vanhatalo, Doust and Burnley (2008a)
suggested that EP can be reduced by approximately 10 W when using a cadence 10 rev-min\(^{-1}\) above the participant’s preferred cadence. Similarly, Dekerle et al. (2014) evaluated the 3-min all-out test in isokinetic mode at both 60 and 100 rev-min\(^{-1}\) and reported a 14% lower EP upon the adoption of the higher cadence. These reductions in EP were attributed to the fact that fast twitch muscle fibres are more susceptible to fatigue when pedalling at higher cadences. This results in a fast decline in power output over the duration of the test, which in turn produces a lower EP during the final 30 s. To overcome this potential limitation of the 3-min cycling test when carried out against fixed resistance, alternative procedures have been suggested including the use of a percentage of body mass value being used to determine the testing resistance (Clark, Murray and Pettitt 2013, Dicks et al. 2016).

It is possible that the methods used to calculate the fixed resistance in the present study affected the validity of the 3-min cycling test at estimating CP and \(W'\) when performed against a fixed resistance. It is suggested that the original method for calculating this resistance (e.g. preferred cadence) is susceptible to error, which may lead to inaccurate testing results. Based on some of the concerns with the 3-min cycling test raised above, it was suggested by Karsten et al. (2016) that CP could be determined from a modified version of the original protocol using 3 TTE tests, each separated by 30 min rest. The results found that CP from this protocol was not significantly different to CP calculated using TTE tests separated by 24 h rest, providing some support for a single testing session to calculate CP. Questions were raised about the validity of \(W'\) calculated from this modified protocol, and although this parameter was not significantly different between protocols, the authors questioned the low levels of agreement. It was concluded that further research was required to fully understand the mechanistic basis of this parameter with one suggestion provided that the 30-min rest period was not long enough for the full reconstitution of \(W'\). With concerns about the validity of the single day CP protocol in calculating both parameters,
more research is required if a single session testing protocol can be used as a valid method in the calculation of both CP and W’.

The estimates of W’ were significantly lower for both isokinetic (~7.1 kJ) and linear modes (~9.2 kJ), with results suggesting that neither testing mode provides a reliable measure of WEP, or a valid estimate of W’. Despite these differences being larger than shown in previous studies, several authors have reported that the 3-min cycling test carried out in both linear and isokinetic modes underestimate W” (Vanhatalo, Doust and Burnley 2007, Karsten et al. 2014a). Previous studies have also suggested that with significant variations in WEP observed between testing sessions, this parameter lacks sensitivity and is, in effect, meaningless (Johnson et al. 2011, Dekerle et al. 2014). Vanhatalo, Doust and Burnley (2007) suggested that these results may be due to the differences in power measurement between the 3-min cycling test and the constant-power tests when using the Lode Excalibur Sport. They explain that during the first 10 s of the 3-min cycling test there is an acceleration of the Lode’s flywheel when performed in the linear mode; however, this acceleration is absent during the constant-power trials used to calculate W” using the original protocol. Vanhatalo, Doust and Burnley (2007) suggested the use of the isokinetic mode or SRM cranks to overcome this problem as they are unaffected by flywheel inertia. The present study found that WEP was significantly lower than W’ when tested in isokinetic mode, supporting the findings of Karsten et al. (2014a) and it might be suggested that the 3-min cycling test is not long enough to fully deplete W’ in all individuals. Based on these suggestions, it is recommended that more research is required with a focus on W’ during exhaustive exercise with trained cyclists. Finally, it should be noted that the original research by Vanhatalo, Doust and Burnley (2007, 2008a, 2008b) was carried out with participants from a mixture of athletic backgrounds that may not have been fully accustomed to all-out cycling. Before the 3-min cycling test can be
used with confidence to estimate CP, it is suggested that additional research is required into the effect cadence has on setting the test resistance.

4.5 Conclusion

The main finding of this study suggests that the 3-min cycling test performed in isokinetic mode is reliable and can also be used to estimate CP calculated from the original CP test. It would appear that although reliable, the 3-min cycling test performed against a fixed resistance does not provide a valid estimate of CP when following the methods used by Vanhatalo, Doust and Burnley (2007). Care should be taken when selecting the testing mode to complete the 3-min all-out cycling test despite the 3-min cycling test being successfully used within applied research and it is suggested that future research should focus on the methods used to set the fixed resistance. Finally, the results also indicate that neither testing mode provides a reliable or valid estimate of $W'$, which would appear to be comparable to previous studies. Cadence selection, the duration of the test and the testing ergometer and mode may all affect the estimates of CP and $W'$. 
5 STUDY TWO: THE 3-MIN TEST IS SENSITIVE TO CHANGES IN CADENCES USING THE LODE EXCALIBUR SPORT ERGOMETER

5.1 Introduction

Aspects of this chapter have been published in the Journal of Sports Sciences (Wright, Bruce-Low and Jobson 2018). The time-consuming nature of the original CP testing protocol led to the development of the 3-min cycling test, and it was initially concluded that this testing protocol would provide a near identical estimation of CP and a similar, albeit slightly lower, estimation of $W'$ (Vanhatalo, Doust and Burnley 2007). More recently, studies have suggested that EP overestimates CP by approximately 5–12%, with WEP significantly underestimating $W'$ when the protocol is performed in isokinetic mode (Dekerle et al. 2014, Karsten et al. 2014a). It was suggested that the difference in testing mode (e.g. linear vs. isokinetic) and participants’ fitness might explain why these studies were unable to replicate the data observed by Vanhatalo, Doust and Burnley (2007) and, therefore, the first study in this thesis was completed to directly compare both testing protocols using the same participants. The results from study one suggested that EP determined when the 3-min cycling test was performed against a fixed resistance (e.g. linear mode) significantly overestimated CP, with a closer estimation of CP observed when performed at a constant cadence (e.g. isokinetic mode). With the results of study one not supporting previous literature, it was suggested that the differences observed between CP and EP are not necessarily attributable to the testing mode used during the 3-min cycling test, but could instead be related to the parameters of the testing protocol, for example, the fixed resistance or cadence.

Research has previously demonstrated that CP is sensitive to changes in cadence when calculated from multiple TTE tests with Barker et al. (2006) concluding that CP is reduced by
approximately 18 W when tests were performed at 100 rev·min⁻¹, compared to 60 rev·min⁻¹.

It has also been demonstrated that the 3-min cycling test is sensitive to small changes in the cadence used to set the ergometer’s fixed resistance (Vanhatalo, Doust and Burnley 2008a). The original 3-min cycling testing protocol requires participants to self-select their preferred cadence, which is subsequently used as part of the calculation to determine the fixed resistance. Concerns were raised in the first study of this thesis that the term ‘preferred cadence’ was ambiguous and it was noted that some participants were unable to provide a definitive cadence when asked. With some participants stating a range of up to 10 rev·min⁻¹, it is not unreasonable that this would affect the estimation of both CP and W’.

For example, if an individual had a 50% Δ of 260 W and suggested their preferred cadence was 90 rev·min⁻¹, they would complete the 3-min cycling test using a linear factor (i.e. fixed resistance) of 0.032 W·min⁻². Based on the assumption that the participants will naturally finish the 3-min cycling test at their preferred cadence, this would result in an EP of approximately 260 W. If, however, the participant naturally cycled faster than 90 rev·min⁻¹ and averaged 100 rev·min⁻¹ over the final 30 s, this would result in an EP of approximately 320 W. This example clearly demonstrates the effect that cadence, and subsequently the fixed resistance, would have on the estimation of CP using the 3-min cycling test when completed using the original testing protocol (Burnley, Doust and Vanhatalo 2006, Vanhatalo, Doust and Burnley 2007).

It has previously been demonstrated that EP is sensitive to changes in the cadence used to set the linear factor (Vanhatalo, Doust and Burnley 2008a). Their findings suggesting that, although unaffected by selecting a lower cadence, EP was reduced by approximately 10 W when using a cadence 10 rev·min⁻¹ above preferred cadence. It was also found that WEP was significantly higher on the adoption of a lower cadence and significantly lower when using a higher cadence. In support of these results, Dekerle et al. (2014) found that cadence
selection affected EP when carried out in isokinetic mode, with a significantly lower EP observed when tested at 100 rev·min⁻¹, compared to 60 rev·min⁻¹. In contrast to Vanhatalo, Doust and Burnley (2008a), Dekerle et al. (2014) found that WEP was significantly increased when tested at a higher cadence. In a similar study, de Lucas et al. (2014) found a significant reduction in EP on the adoption of a higher cadence (100 vs. 60 rev·min⁻¹), but no differences in WEP were observed between cadences. The results from these studies highlight the importance of selecting the correct cadence before carrying out the 3-min cycling test.

With the research described above suggesting that EP is sensitive to changes in cadence, the second experimental study aimed to investigate the effect of cadence on the calculation of EP and WEP from a 3-min cycling test using a repeated-measures study design. It was hypothesised that 1) higher cadences would result in a reduction in EP, and 2) that higher cadences would result in a reduction in WEP.

5.2 Methods

5.2.1 Participants

Ten male cyclists (mean ± SD: age 30 ± 5 years, body mass 78.6 ± 6.6 kg, MAP 368 ± 29 W, \(\dot{V}O_{\text{peak}}\) 4.7 ± 0.4 L·min⁻¹) volunteered to take part in this study. All participants provided written informed consent and completed a PAR-Q prior to testing. Participants took part in a total of eight tests to calculate GET, MAP, \(\dot{V}O_{\text{peak}}\), CP, \(W'\), and the estimates EP and WEP, with each testing session separated by a minimum of 48 h. Other than test one, for determination of GET, \(\dot{V}O_{\text{peak}}\) and MAP, all tests were completed out in a randomised order. Strong verbal encouragement was provided during each test but no feedback regarding heart rate, power output or time was provided.
5.2.2 GET, MAP and $\dot{V}O_{2}\text{peak}$ Protocols

Each participant completed a maximal incremental ramp test (20 W·min$^{-1}$) to calculate GET, MAP and $\dot{V}O_{2}\text{peak}$ (Davis et al. 1982). Throughout the test, breath-by-breath expired air (MasterScreen CPX, Viasys, Germany) and heart rate (RCX5, Polar, Finland) were recorded at 5-s intervals. On completion of the test, a capillary blood lactate sample (Biosen C-line, EKF Diagnostics, Germany) was taken from the fingertip.

5.2.3 Original Critical Power Test

Following a 10-min warm up, each participant completed three separate TTE tests at 80, 100 and 105% MAP (Karsten et al. 2014a), with each test terminated when the cadence dropped by more than 10 rev·min$^{-1}$ below the participant’s preferred cadence for more than 5 s. Consistent with Vanhatalo, Doust and Burnley (2007) and Karsten et al. (2014a), CP and W$'$ were calculated using the linear power-1/time mathematical model.

5.2.4 3-min Cycling Tests

On separate days, EP and WEP were calculated from four 3-min cycling tests. All participants had experience of the testing protocol from study one and had completed a minimum of four tests in the previous 12 months. For each test, a fixed resistance was used in line with the protocol described by Vanhatalo, Doust and Burnley (2007) and was calculated using four different cadences:

3. Preferred cadence $+5$ rev·min$^{-1}$ (EP$+5$ and WEP$+5$).
4. Preferred cadence $+10$ rev·min$^{-1}$ (EP$+10$ and WEP$+10$).

Each 3-min cycling test started with an unloaded period of cycling for 30 s with participants instructed to increase their cadence to approximately 110 rev·min$^{-1}$ in the final 10 s.
Following a countdown, participants were instructed to cycle maximally from a seated position and were encouraged to reach peak power output within the first 5 s of the 3-min cycling tests. It was clearly explained that maximal exertion should be given throughout the test and that the test should not be paced. Heart rate and \( \text{VO}_2 \) were measured throughout each test with a post-test capillary blood lactate sample taken immediately upon completion.

5.2.5 Statistical Analyses

Shapiro-Wilk tests of normality were carried out on all data prior to analysis with all data normally distributed \((P > 0.05)\). A one-way repeated-measures ANOVA and LoA were used to compare the differences between CP with EP, and \( W' \) with WEP at each cadence, with relationships measured using Pearson’s product moment correlation coefficients. A one-way repeated-measures ANOVA was also used to compare EP and WEP between testing sessions, with ES calculated using Cohen’s \( d \); trivial \((<0.19)\), small \((0.20–0.49)\), medium \((0.50–0.79)\) and large \((>0.80)\). The error associated with predicting EP and WEP from linear regression methods was measured using SEE. All data are reported as mean ± SD with statistical significance accepted at \( P < 0.05 \).

5.3 Results

Comparisons between \( \text{VO}_2 \text{peak} \), peak power, EP, peak cadence, end cadence, and WEP during each 3-min all-out test are displayed in Table 5.1. The mean cadences observed during the incremental ramp test and the three TTE tests can be found in Table 5.2. A one-way repeated-measures ANOVA showed significant differences between EP-preferred and CP \((297 ± 26 \text{ W vs. } 268 ± 23 \text{ W}, P < 0.001, 95\% \text{ LoA of } 30 ± 21 \text{ W}, \text{ES} = 1.18)\), EP−5 and CP \((304 ± 24 \text{ W vs. } 268 ± 23 \text{ W}, P < 0.001, 95\% \text{ LoA of } 36 ± 23 \text{ W}, \text{ES} = 1.53)\), and between EP+5 and CP \((290 ± 28 \text{ W vs. } 268 ± 23 \text{ W}, P = 0.002, 95\% \text{ LoA of } 23 ± 23 \text{ W}, \text{ES} = 0.86)\). At the highest cadence, results
showed no significant difference between EP+10 and CP (278 ± 31 W vs. 268 ± 23 W, \( P = 0.331, 95\% \) LoA of 11 ± 26 W, ES = 0.37) (Figure 5.1).

**Table 5.1** Mean values (± SD) observed during each 3-min cycling test.

<table>
<thead>
<tr>
<th></th>
<th>Preferred Cadence</th>
<th>Preferred Cadence</th>
<th>Preferred Cadence</th>
<th>Preferred Cadence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>−5 rev·min⁻¹</td>
<td>+5 rev·min⁻¹</td>
<td>+10 rev·min⁻¹</td>
<td></td>
</tr>
<tr>
<td>( \dot{V}O_2 )peak (L·min⁻¹)</td>
<td>4.8 ± 0.4</td>
<td>4.7 ± 0.6</td>
<td>4.8 ± 0.5</td>
<td>4.7 ± 0.6</td>
</tr>
<tr>
<td>Peak power (W)</td>
<td>873 ± 182</td>
<td>932 ± 190</td>
<td>798 ± 157</td>
<td>784 ± 141</td>
</tr>
<tr>
<td>EP (W)</td>
<td>297 ± 26</td>
<td>304 ± 24</td>
<td>290 ± 28</td>
<td>278 ± 31</td>
</tr>
<tr>
<td>Preferred cadence (rev·min⁻¹)</td>
<td>91.0 ± 1.6</td>
<td>86.0 ± 1.6</td>
<td>96.0 ± 1.6</td>
<td>101.0 ± 1.6</td>
</tr>
<tr>
<td>Peak cadence (rev·min⁻¹)</td>
<td>157.0 ± 14.6</td>
<td>155.8 ± 13.0</td>
<td>159.3 ± 13.8</td>
<td>164.7 ± 11.8</td>
</tr>
<tr>
<td>End cadence (rev·min⁻¹)</td>
<td>93.0 ± 4.0</td>
<td>90.1 ± 2.2</td>
<td>98.3 ± 2.8</td>
<td>101.6 ± 3.4</td>
</tr>
<tr>
<td>WEP (kJ)</td>
<td>11.2 ± 4.5</td>
<td>12.6 ± 4.0</td>
<td>11.0 ± 4.4</td>
<td>10.9 ± 4.8</td>
</tr>
</tbody>
</table>

*Significantly different from preferred cadence (\( P < 0.05 \)).

**Figure 5.1** Bland-Altman plots showing the limits of agreement between (a) EP-preferred and CP, (b) EP−5 and CP, (c) EP+5 and CP, and (d) EP+10 and CP. The solid line represents the mean difference in power output, and the dashed line represents the 95\% limits of agreement.
Significant differences were seen between WEP-preferred and $W'$ ($11.2 \pm 4.5 \text{ kJ}$ vs. $20.5 \pm 5.1 \text{ kJ}$, $P < 0.001$, 95% LoA of $-8.6 \pm 10.1 \text{ kJ}$, ES = 1.93), WEP−5 and $W'$ ($12.6 \pm 4.0 \text{ kJ}$ vs. $20.5 \pm 5.1 \text{ kJ}$, $P = 0.017$, 95% LoA of $-7.7 \pm 10.8 \text{ kJ}$, ES = 4.0), WEP+5 and $W'$ ($11.0 \pm 4.4 \text{ kJ}$ vs. $20.5 \pm 5.1 \text{ kJ}$, $P = 0.003$, 95% LoA of $-9.4 \pm 10.4 \text{ kJ}$, ES = 1.99), and between WEP+10 and $W'$ ($10.9 \pm 4.8 \text{ kJ}$ vs. $20.5 \pm 5.1$, $P = 0.012$, 95% LoA of $-8.9 \pm 11.8 \text{ kJ}$, ES = 1.94) (Figure 5.2).

![Bland-Altman plots](image)

**Figure 5.2** Bland-Altman plots showing the limits of agreement between (a) WEP-preferred and $W'$, (b) WEP−5 and $W'$, (c) WEP+5 and $W'$, and (d) WEP+10 and $W'$. The solid line represents the mean difference in power output, and the dashed line represents the 95% limits of agreement.

The SEE and correlation coefficients between CP with EP, and between $W'$ with WEP at each cadence are shown in Figure 5.3 and Figure 5.4. These results show a large correlation between CP and EP at all tested cadences ($r = 0.76–0.89$). The results also show a medium correlation between $W'$ and WEP-preferred and WEP−5 ($r = 0.35–0.46$), and a small correlation between $W'$ and WEP+5 and WEP+10 ($r = 0.17–0.22$).
Figure 5.3 Relationships between (a) EP-preferred and CP, (b) EP−5 and CP, (c) EP+5 and CP, and (d) EP+10 and CP.

Figure 5.4 Relationships between (a) WEP-preferred and W′, (b) WEP−5 and W′, (c) WEP+5 and W′, and (d) WEP+10 and W′.
Results from a one-way repeated-measures ANOVA showed no significant differences between EP-preferred and EP−5 (297 ± 26 W vs. 304 ± 24 W, \( P = 0.173 \), ES = 0.28) or between EP-preferred and EP+5 (297 ± 26 W vs. 290 ± 28 W, \( P = 0.237 \), ES = 0.26); however, significant differences were seen between EP-preferred and EP+10 (297 ± 26 W vs. 278 ± 31 W, \( P = 0.001 \), ES = 0.66). It should also be noted that significant differences were seen between EP+10 and all other cadences (\( P < 0.05 \)). No significant differences were found between WEP-preferred and WEP−5 (11.2 ± 4.5 kJ vs. 12.6 ± 4.0 kJ, \( P = 0.934 \), ES = 0.33), WEP+5 (11.2 ± 4.5 kJ vs. 11.0 ± 4.4 kJ, \( P = 1.000 \), ES = 0.45) or with WEP+10 (11.2 ± 4.5 kJ vs. 10.9 ± 4.8 kJ, \( P = 1.000 \), ES = 0.64). Furthermore, no significant differences were seen for WEP between any of the cadences (\( P > 0.05 \)). Oxygen uptake during the 3-min cycling test is highlighted in Figure 5.5 and demonstrates how 95% ramp test \( \overline{V}O_2 \)peak was attained within the first 90 s and then maintained for the duration of the test in line with the recommendations defined by Jones et al. (2010).

![Figure 5.5](image-url)  
*Figure 5.5* Example \( \overline{V}O_2 \) uptake observed during the 3-min cycling test. Preferred cadence = closed circles, preferred cadence = 5 rev·min\(^{-1}\) = open circles, preferred cadence +5 rev·min\(^{-1}\) = closed squares, and preferred cadence +10 rev·min\(^{-1}\) = open squares.
Table 5.2 highlights the mean cadence, \( \text{VO}_{2\text{peak}} \) and TTE during each testing session. No significant differences were seen between \( \text{VO}_{2\text{peak}} \) observed during the ramp test and the 80% MAP TTE (4.8 ± 0.4 L·min\(^{-1}\) vs. 4.6 ± 0.4 L·min\(^{-1}\), \( P = 0.820, \text{ES} = 0.50 \)), 100% MAP TTE (4.8 ± 0.4 L·min\(^{-1}\) vs. 4.5 ± 0.6 L·min\(^{-1}\), \( P = 1.000, \text{ES} = 0.57 \)) or 105% MAP TTE (4.8 ± 0.4 L·min\(^{-1}\) vs. 4.6 ± 0.5 L·min\(^{-1}\), \( P = 1.000, \text{ES} = 0.44 \)) with 95% ramp test \( \text{VO}_{2\text{peak}} \) observed for all TTE conditions. The \( R^2 \) value for the linear power-1/time mathematical model ranged from 0.97–1.00 for all participants with a SEE of 0.3–15.8 W for CP and 0.6–4.5 kJ for \( W' \) observed.

<table>
<thead>
<tr>
<th>Testing session</th>
<th>Cadence (rev·min(^{-1}))</th>
<th>( \text{VO}_{2\text{peak}} ) (L·min(^{-1}))</th>
<th>TTE (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{VO}_{2\text{peak}} ) ramp test</td>
<td>93.4 ± 4.0</td>
<td>4.7 ± 0.4</td>
<td>675 ± 87</td>
</tr>
<tr>
<td>80% MAP</td>
<td>90.7 ± 7.0</td>
<td>4.6 ± 0.4</td>
<td>714 ± 143</td>
</tr>
<tr>
<td>100% MAP</td>
<td>95.4 ± 4.5</td>
<td>4.5 ± 0.6</td>
<td>203 ± 40</td>
</tr>
<tr>
<td>105% MAP</td>
<td>96.6 ± 3.9</td>
<td>4.6 ± 0.5</td>
<td>166 ± 31</td>
</tr>
</tbody>
</table>

5.4 Discussion

The results of the present study suggest that EP calculated from the 3-min cycling test is affected by the cadence used to set the fixed resistance, with a reduction in EP observed at higher cadences. Results also suggest that selecting a cadence 10 rev·min\(^{-1}\) above preferred cadence provides the best estimation of CP, with EP-preferred, EP−5 and EP+5 significantly overestimating CP. Additionally, the results suggest that WEP is unaffected by cadence, with \( W' \) significantly underestimated at all cadences tested. The results of this study highlight the importance of selecting the correct cadence when setting the fixed resistance prior to undertaking the 3-min cycling test. The first hypothesis that higher cadences used during a 3-min cycling test would elicit a reduction in EP is accepted; however, the second hypothesis stating that a reduction would also be seen for WEP is rejected.
The 3-min cycling test has been extensively investigated (Francis et al. 2010, Johnson et al. 2011, de Lucas et al. 2014, Dekerle et al. 2014, Dicks et al. 2016) with some recent studies suggesting that EP significantly overestimates CP (Bergstrom et al. 2014, Karsten et al. 2014a, Wright, Bruce-Low and Jobson 2017). These studies raise questions about the protocols used when performing the 3-min cycling test. Concerns about the 3-min cycling test have also been raised by Mattioni Maturana et al. (2016), who, despite concluding that the mean difference between CP and EP was not significantly different (253 ± 44 W vs. 250 ± 51 W), suggested that care should be taken when using this test due to the wide LoA observed from the Bland-Altman plots.

The original research by Vanhatalo, Doust and Burnley (2007) concluded that the 3-min cycling test provided a reliable measure of EP and WEP and an almost identical estimation of CP. In a separate study, it was noted that EP is reduced by approximately 10 W upon the selection of a higher cadence (preferred +10 rev·min⁻¹), but that it is unaffected when tested at a slightly lower cadence (preferred −5 rev·min⁻¹) (Vanhatalo, Doust and Burnley 2008a). The results of the present study support these findings, although slightly larger reductions in EP of approximately 20 W were observed at the highest cadence (+10 rev·min⁻¹). Results also suggest that WEP is less sensitive and remains consistent across cadences supporting the research of Vanhatalo, Doust and Burnley (2008a) and Chidnok et al. (2013), who reported that WEP was unaffected by pacing during a 3-min cycling test. The effect of cadence on EP and WEP has also been investigated when using the isokinetic ergometer mode, with results showing that EP is reduced upon the adoption of a higher cadence (de Lucas et al. 2014, Dekerle et al. 2014). With slightly larger differences of approximately 30–37 W observed between conditions when tested in isokinetic mode, it should be noted that a greater range in cadences were used (60–100 rev·min⁻¹) in the studies by Dekerle et al. (2014) and de Lucas et al. (2014) when compared to the present study.
With results from the present study demonstrating that EP is reduced at higher cadences, the importance of selecting the correct cadence when performing the 3-min cycling test is highlighted. It could be assumed that the preferred cadences verbally suggested by each participant in the present study were not high enough to elicit similar results to those reported previously (Vanhatalo, Doust and Burnley 2007). It can be seen from Table 5.2 that the participants naturally chose a higher cadence for the shorter, and higher power output TTE tests (89.5 ± 4.6 rev·min⁻¹ at 80% MAP compared to 96.2 ± 3.4 rev·min⁻¹ at 105% MAP), differing significantly from their self-selected preferred cadence of 91.0 ± 1.6 rev·min⁻¹. Abbiss et al. (2009) suggested that, for ultra-endurance events, a cadence of 70–90 rev·min⁻¹ may be optimal due to the reduced energy cost and increased cycling economy observed at lower cadences. For endurance events and short duration sprint events, however, cadences of 90–100 and 110 rev·min⁻¹, respectively, may be advised to increase power output (Sargeant, Hoinville and Young 1981, Abbiss, Peiffer and Laursen 2009).

The effect of cadence on muscular fatigue has been extensively investigated in the scientific literature, with higher cadences leading to a faster decline in muscular fatigue (Beelen and Sargeant 1991, Hill et al. 1995, Vanhatalo, Doust and Burnley 2008a). Due to the physiological basis of the 3-min cycling test, it is imperative that the W′ is exhausted within the first 150 s of the test. A faster decline in fatigue is likely to result in a lower EP, which, in turn, may provide a more accurate estimate of CP. McCartney et al. (1985) found that the decline in average power observed during a 30-s maximal sprint was less at 60 rev·min⁻¹ compared to 140 rev·min⁻¹. Vanhatalo, Doust and Burnley (2008b) have suggested that an increase in fatigue at higher cadences could be due to the fatiguing qualities of type I and II muscle fibres. It was also suggested that the high cadences observed during the initial stages of the 3-min cycling test, especially during the high cadence condition, results in sub-optimal cadences for peak power production. Dekerle et al. (2014) also observed reductions in EP
when using a higher cadence during the 3-min cycling test, suggesting that fast twitch muscle fibres are less fatigue resistant. These results highlight the challenges faced when using the participant’s preferred cadence to set the fixed resistance during the 3-min cycling test. The effect of cadence on muscular fatigue may also influence the original CP protocol with Green, Bishop and Jenkins (1995) reporting that $W’$ is significantly increased if the end-test cadence is reduced from 70 to 60 rev·min$^{-1}$.

To standardise testing sessions for experimental studies one, two and five of this thesis, TTE tests were terminated when the participants’ cadence dropped by more than 10 rev·min$^{-1}$ below their preferred cadence; however, they were not instructed to maintain a set cadence throughout each test. Table 5.2 highlights the differences in mean cadence during each test and, with a difference of approximately 7 rev·min$^{-1}$ between the 80, 100 and 105% TTE tests, it is reasonable to assume that this could affect the calculations of both CP and $W’$. It is also possible that the accuracy of the original CP protocol may have been affected by the selection of only three TTE tests, and although three TTE tests have successfully been used to calculate CP and $W’$ (de Lucas et al. 2014), some authors recommend four or more TTE tests (Poole et al. 1988).

In a recent study by Mattioni Maturana et al. (2018), the authors concluded that the mathematical model, number and duration of TTE tests used can affect the calculation of CP and $W’$. Despite their findings supporting the use of the linear power-1/time mathematical model from three TTE tests, it was reported that CP might vary by approximately 12 W depending on the duration of each test. All participants in the present study reached exhaustion within 2–15 min for each TTE test, as stipulated by Jones et al. (2010); however, the results from the study by Mattioni Maturana et al. (2018) suggest that slightly longer TTE tests should be included (e.g. ≤20 min) to ensure accurate estimations of CP. Participants
within the present study also reached a post-test blood lactate above 8 mmol·L⁻¹ and an end-test RER of >1.15 during all TTE tests, suggesting that a maximal effort was given during each TTE. A limitation of the present study is that a CP validation test to ensure that a physiological steady-state had been established was not completed. Based on the concerns above it is reasonable to suggest that the linear power-1/time mathematical model may not have provided the most accurate method for calculating CP. Without completing a physiological validation test, it is not possible to say with certainty that the original CP protocol or 3-min cycling test provided a true estimation of CP and, therefore, the demarcation between the heavy and severe exercise intensity domains. This is a common limitation within the scientific literature, and it should also be noted that the original research by Vanhatalo, Doust and Burnley (2007) on the 3-min cycling test was not physiologically validated.

Alternative testing protocols have been suggested based on the sensitivity of the 3-min cycling test to the cadence used to set the fixed resistance, along with the requirement of an additional testing session to calculate GET and \( \dot{V}O_{2\text{peak}} \) (Clark, Murray and Pettitt, Dicks et al. 2016). Furthermore, Clark, Murray and Pettitt (2013) noted that some participants failed to complete the 3-min cycling test when the resistance was set according to the protocol described by Vanhatalo, Doust and Burnley (2007) and investigated the possibility of setting the fixed resistance using a percentage of body mass (%BM), taking into consideration the fitness levels of each participant: 3%BM for recreationally active, 4%BM for anaerobic and aerobic athletes and 5%BM for endurance athletes. The results from their study provided evidence to support the use of %BM for setting the fixed resistance as not only does this method provide accurate estimates of CP and \( W' \), but it also removes the ambiguity of selecting a preferred cadence. Dicks et al. (2016) have also investigated an alternative testing protocol by estimating 50% \( \Delta \) from a self-reported physical activity scale. Both studies concluded that CP and \( W' \) could be estimated without the need to initially calculate GET and
\( \text{VO}_{2\text{peak}} \); however, some concerns remain about the reliance on calculating the fixed resistance based on the requirement of each participant to self-select their current fitness level.

The 3-min cycling test has been demonstrated to provide a valid estimation of CP, but there remains a concern about its sensitivity to the cadence used to set the fixed testing resistance. It is recommended that future research investigates the differences in cadences on a wider range of cyclists, from novice to elite, and to understand the effect these have on the estimation of CP. It is suggested that this information may help inform a more definitive method for identifying the participant’s preferred cadence. It is also suggested that the method for depleting \( W' \) during all-out testing protocols is investigated in more detail to potentially refine the original 3-min cycling test. Finally, it is essential that future research includes a CP validation test to ensure that the results obtained have a practical application and demonstrate that CP demarcates the boundary between the heavy and severe exercise intensity domains.

5.5 Conclusion

The key finding of this study suggests that the 3-min cycling test is sensitive to changes in cadence. Results show that EP was reduced upon the adoption of higher cadences; an increase of 10 rev-min\(^{-1} \) above preferred cadence resulted in an EP similar to CP calculated from the original CP protocol. Results also supported previous research to suggest that WEP is not affected by changes in cadence, although it remains significantly lower than \( W' \). Future research should investigate how an athlete’s preferred cadence is determined prior to using the 3-min cycling test or should attempt to refine the original protocol to ensure that cadence does not affect the calculation of CP. Finally, a CP validation test should be included in all future research.
6 STUDY THREE: RELIABILITY AND VALIDITY OF THE POWERTAP P1 AND GARMIN VECTOR 2 PEDALS

6.1 Introduction

The results from experimental studies one and two provide some evidence to suggest that the 3-min cycling test can be used to estimate CP; however, they also highlight concerns about the sensitivity of this protocol to the testing mode, ergometer and fitness of the participant. Study two suggested that the 3-min cycling test is sensitive to the cadence used to set the fixed resistance, with a higher than preferred cadence resulting in the best estimation of CP. When the fixed resistance was set using a cadence of 10 rev-min\(^{-1}\) above preferred cadence, EP was not significantly different to CP, and consistent to previous literature (Dekerle et al. 2014), WEP remained significantly lower than \(W'\). A direct consequence of WEP significantly underestimating \(W'\) is an overestimation of CP, and it is suggested that the 3-min cycling test could be modified to overcome this issue using a novel all-out cycling test. The proposed novel all-out testing protocol (detailed in experimental study five) requires participants to cycle until muscular failure using the Lode Excalibur Sport’s hyperbolic mode, immediately followed by a period of maximal cycling in isokinetic mode.

During data collection for studies one and two, concerns were raised about the Lode Excalibur Sport, which needed to be addressed before testing the novel all-out protocol. Firstly, the exported data when testing in the hyperbolic mode is limited as the Lode software assumes that the set power output is constant during cycling and not affected by the natural variation in a cyclist’s cadence (Chapman et al. 2008). Secondly, when a protocol includes two phases (e.g. a phase in hyperbolic mode, immediately followed by an isokinetic phase, as proposed in the novel all-out testing protocol), the exported power output often reports
a power output of 0 W between the two phases for between 2–4 s. Finally, the manufacturer states that the Lode Excalibur Sport is only accurate in the hyperbolic mode when cycling above 30 rev·min⁻¹ which is likely to affect the results of the proposed novel protocol, with the participants required to cycle until muscular failure (i.e. <30 rev·min⁻¹).

Figure 6.1 compares the exported power output between the Lode Excalibur Sport and a set of PowerTap P1 pedals during a test to muscular failure in hyperbolic mode, followed by a brief period of cycling in isokinetic mode. A drop in power output can be observed in the P1 pedals as muscular fatigue develops in the final stages of the hyperbolic mode phase (~ 75 s), with this reduction not reflected in the exported data from the Lode Excalibur Sport. Additionally, the power output from the Lode Excalibur Sport is exported as 0 W when switching between testing phases, and this limitation is not observed for the P1 pedals.

![Figure 6.1](image-url)  
*Figure 6.1* Comparison of exported power output data from the PowerTap P1 pedals (solid line) and Lode Excalibur Sport (dashed line).
Due to the limitations of the Lode Excalibur Sport mentioned above, it was decided that power output for the final study would be measured using a pedal-based power measurement device installed onto the testing ergometer. At study initiation, two commonly used pedal-based power meters were available on the market: the PowerTap P1 pedals (P1) and the Garmin Vector pedals (V2).

Previous literature has raised some concerns about the reliability and validity of pedal-based power meters, and due to the lack of research using the P1 and V2 pedals, a reliability and validity study was required before they could be used in study five with confidence. A previous study by Novak and Dascombe (2016) had investigated the validity of the original Garmin Vector pedals (v1.0) with findings to suggest that they overestimated power output, with a TEE of 3.0–3.8% when compared to an SRM Powermeter. The authors suggested that the small difference in power output observed between the two systems was likely due to the location of torque measurement. With the pedals measuring torque directly at the foot, it is not unreasonable to suggest that some dissipation in force is likely to occur before the measurement is taken at the crank (e.g. SRM Powermeter). In conclusion, Novak and Dascombe (2016) recommended that the pedals could be used to monitor the performance of well-trained cyclists but stressed the importance of regular checks against a known “gold standard” system.

Before completing the final study in this thesis and testing the hypothesis that a novel all-out testing protocol would provide reliable and valid estimates of CP and W', it was vital that the power pedals used demonstrated test-retest reliability and concurrent validity. Using a repeated-measures study design, the aims of study three were 1) to evaluate agreement between the P1 and V2 power pedals and the Lode Excalibur Sport, and 2) to investigate the reliability of the P1 and V2 power pedals. It was hypothesised that 1) the P1 pedals would
provide reliable and valid data at all tested power outputs when compared to the Lode Excalibur Sport ergometer, and 2) the V2 pedals would provide reliable and valid data at all tested power outputs when compared to the Lode Excalibur Sport ergometer.

6.2 Methods

6.2.1 Participants
Ten male cyclists (mean ± SD: age 35 ± 6 years, body mass 80.8 ± 8.8 kg, stature 1.83 ± 0.05 m) volunteered to take part in this study. All participants provided written informed consent and completed a PAR-Q prior to testing. Each participant completed the testing procedure on four occasions, two using the P1 (P1, PowerTap, USA) pedals and two using the V2 (Vector 2, Garmin, USA) pedals. All testing was carried out on an electronically-braked cycle ergometer (Excalibur Sport, Lode, The Netherlands) with testing sessions carried out in a randomised order. During all testing sessions, the participants could see the ergometer’s cadence monitor but visual feedback on power output and elapsed time were not provided.

6.2.2 Experimental Procedures
Following a 10-min warm up, participants completed four 5-min sub-maximal cycling bouts (100, 150, 200 and 250 W) using the ergometer’s hyperbolic mode, each separated by a 5-min recovery period at 50 W. The participants were then given a 15-min active recovery period at 100 W before completing a 2-min maximal TT test against a fixed resistance. This resistance was set using the Lode Excalibur Sport’s ‘linear’ mode according to the equation: resistance = power output/cadence². The default for this resistance is 0.042 W·min⁻², which would elicit a power output of approximately 340 W if cycling at 90 rev·min⁻¹. Following a further 15-min recovery period, the participants were required to complete two 10-s maximal sprints, each separated by a 2-min recovery period. Each sprint was carried out using the ergometer’s ‘Wingate’ mode, with the torque factor set to 0.7 Nm·kg⁻¹.
6.2.3  Statistical Analyses

Shapiro-Wilk tests of normality made clear that data did not meet the assumption of normality ($P < 0.05$) resulting in non-parametric analyses. Comparisons between the Lode Excalibur Sport and each power pedal were made using a Mann Whitney-U test. ES were calculated using Cohen’s $d$: trivial ($<0.19$), small (0.20–0.49), medium (0.50–0.79) and large (>0.80) (Cumming 2014). Agreement between the Lode Excalibur Sport and each pedal was assessed using LoA and Pearson’s product moment correlation coefficients during the 2-min TT and maximal sprints. Predicted vs. residual values for power output were plotted to check for heteroscedasticity for the P1 and V2 pedals. Test-retest reliability was measured using $CV$ and typical error of measurement (TEM) and upper and lower 95% confidence limits. Statistical significance was set to $P = 0.05$, with all data reported as mean ± SD.

6.3  Results

A Mann-Whitney-U test identified significant differences between the Lode Excalibur Sport and the P1 pedals at 100 W (100 ± 0 W vs. 100 ± 2 W, $U = 100$, $z = -3.077$, $P = 0.006$), 150 W (150 ± 0 W vs. 151 ± 2 W, $U = 100$, $z = -2.969$, $P = 0.006$), 200 W (200 ± 0 W vs. 202 ± 3 W, $U = 80$, $z = -3.476$, $P = 0.001$), and 250 W (250 ± 0 W vs. 252 ± 2 W, $U = 100$, $z = -2.900$, $P = 0.006$). Significant differences were also seen during the all-out sprints (964 ± 111 W vs. 1026 ± 116 W, $U = 498$, $z = -2.322$, $P = 0.020$, 95% LoA of −62 ± 195 W, ES = 0.55) (Figure 6.3a). No significant differences between the Lode Excalibur Sport and P1 were observed during the 2-min all-out TT (403 ± 57 W vs. 399 ± 55 W, $U = 187$, $z = -0.365$, $P = 0.718$, 95% LoA of 4 ± 18 W, ES = 0.07) (Figure 6.2a).

Significant differences were seen between the Lode Excalibur Sport and the V2 pedals at 100 W (100 ± 0 W vs. 104 ± 4 W, $U = 50$, $z = -4.393$, $P < 0.001$), 150 W (150 ± 0 W vs. 157 W ± 5.3, $U = 40$, $z = -4.628$, $P < 0.001$), 200 W (200 ± 0 W vs. 208 ± 6 W, $U = 20$, $z = -5.208$, $P = 0.001$),
and 250 W (250 ± 0 W vs. 262 ± 8 W, $U = 20, z = -5.205, P < 0.001$). A significant difference was also seen between the Lode Excalibur Sport and the V2 pedals during the all-out sprint performance ($974 ± 101$ W vs. $1026 ± 96$ W, $U = 790, z = -2.077, P = 0.013, 95\%$ LoA of $-51 ± 196$ W, ES = 0.53) (Figure 6.3b). No significant differences were seen between the Lode Excalibur Sport and the V2 pedals during the 2-min all-out time trial ($401 ± 46$ W vs. $402 ± 48$ W, $U = 190, z = -0.284, P = 0.779, 95\%$ LoA of $-1 ± 26$ W, ES = 0.03) (Figure 6.2b).

![Figure 6.2](image.png)

**Figure 6.2** Bland-Altman plots showing the limits of agreement between the Lode Excalibur Sport and (a) the P1 pedals, and (b) the V2 pedals during a 2-min TT. The solid line represents the mean difference in power output, and the dashed line represents the 95% limits of agreement.

![Figure 6.3](image.png)

**Figure 6.3** Bland-Altman plots showing the limits of agreement between peak power output of the Lode Excalibur Sport and (a) the P1 pedals, and (b) the V2 pedals during a 10-s all-out sprint. The solid line represents the mean difference in power output, and the dashed line represents the 95% limits of agreement.

The CV and TEM for the P1 pedals ranged from 0.6–1.3% and 0.8–8.0 W, respectively, during the sub-maximal cycling bouts. For the V2 pedals, the CV and TEM ranged from 0.7–2.7% and
2.6–8.2 W, respectively (Table 6.1). Figure 6.4 highlights the heteroscedastic nature of power output data recorded by the P1 and V2 pedals, with an increase in error observed at higher power outputs.

### Table 6.1 Coefficient of variation and absolute typical error of measurement between testing sessions 1 and 2 including 95% confidence limits.

<table>
<thead>
<tr>
<th>PowerTap P1</th>
<th>Garmin Vector 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV (%)</td>
<td>TEM (W)</td>
</tr>
<tr>
<td>100 W</td>
<td>0.6 (0.2–1.0)</td>
</tr>
<tr>
<td>150 W</td>
<td>0.7 (0.5–1.0)</td>
</tr>
<tr>
<td>200 W</td>
<td>0.7 (0.3–1.10)</td>
</tr>
<tr>
<td>250 W</td>
<td>0.6 (0.4–1.2)</td>
</tr>
<tr>
<td>2-min TT</td>
<td>1.3 (0.4–2.2)</td>
</tr>
<tr>
<td>All-out Sprint</td>
<td>4.2 (1.8–6.7)</td>
</tr>
</tbody>
</table>

**Figure 6.4** Plot of predicted vs. residual (Lode – pedals) values for P1 pedals (open circles) and V2 pedals (closed circles).

The Pearson’s product moment correlation demonstrated a large correlation between the Lode and P1 pedals ($r = 0.98, P < 0.001$) (Figure 6.5a), and between the Lode and V2 pedals...
was \( r = 0.92, P < 0.001 \) (Figure 6.5b) during the 2-min TT. During the sprint performance, a medium correlation was observed between the Lode and P1 pedals \( (r = 0.35, P < 0.001) \) (Figure 6.5c), with a small correlation observed between the Lode and V2 pedals \( (r = 0.22, P = 0.002) \) (Figure 6.5d).

![Figure 6.5 Relationships between the Lode Excalibur Sport and (a) the P1 pedals, and (b) the V2 pedals during a 2-min TT and between the Lode Excalibur Sport and (c) the P1 pedals, and (d) the V2 pedals during a 10-s all-out sprint.](image)

### 6.4 Discussion

The results of the present study suggest that the PowerTap P1 and Garmin Vector 2 pedals provide reliable data during sub-maximal cycling and, although the P1 pedals were significantly different to the Lode Excalibur Sport 100–250 W, the difference at each power output was <2 W. In comparison, the V2 pedals were between 4–12 W different to the Lode Excalibur Sport during sub-maximal power outputs. During all-out sprint performance, the P1 and V2 pedals both appear to significantly overestimate power output by approximately
60 W, with a TEM of 50.3 W (P1) and 74.0 W (V2), raising some concerns about the use of these pedals during all-out sprinting. The hypotheses that both the P1 and V2 pedals would provide reliable and valid data across all tested power outputs have been rejected.

The CV of the P1 (0.6–1.3%) and V2 (0.7–2.7%) pedals during the sub-maximal intervals is comparable, but slightly lower than a recent study by Pallarés and Lillo-Bevia (2018) who concluded that the P1 pedals produced a CV of 2.4–3.7% when cycling at 70–100 rev-min⁻¹. These authors also reported that the mean CV of the P1 pedals was reduced to 1.6% when the pedals were tested in a standing position, but this is potentially due to the limited range of power outputs tested (250–450 W), rather than the change in cycling position. The results of the present study are also comparable to alternative systems, with Bertucci et al. (2005) reporting the SRM Powermeter to have a CV of 0.7–2.1% at sub-maximal intensities and the PowerTap (hub) to have a CV of 0.9–2.9% between testing sessions. In separate studies, the ErgomoPro was found to have a slightly higher CV, with Kirkland et al. (2008) observing a CV of 2.3%, and Duc, Villerius and Bertucci (2007) observing a CV of 4.1% between testing sessions at power outputs of less than 450 W. According to Hopkins (2000b), the CV should not exceed 5% and in the present study, the P1 pedals met this criterion for all tested power outputs. Similarly, the V2 pedals met this criterion for all sub-maximal power outputs but slightly exceeded the 5% limit during all-out sprinting, with a CV of 5.6% observed.

Figure 6.4 highlights the heteroscedastic nature of power output data recorded by the P1 and V2 pedals, with an increase of error observed at higher power outputs. The location of torque measurements can potentially explain these results and it is reasonable to expect small differences between devices if they measure torque at different locations (e.g. crank, hub or pedal). It has been suggested that the force applied by the cyclist’s foot may dissipate through the pedal, crankset and chain drive, resulting in some force being absorbed at the
pedals prior to the measurement of the Lode Excalibur Sport at the crank (Bertucci et al. 2005, Hopker and Jobson 2012, Novak and Dascombe 2016). Based on the theory that the applied force would potentially dissipate from the pedal to the crank, it could be expected that the P1 and V2 pedals would measure higher power outputs than the Lode Excalibur Sport.

It is known that temperature can affect the accuracy of power measurement (Gardner et al. 2004, Passfield et al. 2016), and to control for this, the laboratory was set to 18 ± 1 °C during all testing sessions. The accuracy of measurement is also known to be affected by the location at which the strain gauges measure torque. Some pedal-based systems (e.g. Garmin Vector) use strain gauges located within the axle, and these are known to be sensitive to the torque applied during installation and, therefore, the manufacturer recommends that the V2 pedals are installed to a torque of 34–40 Nm to take this into account. Care was taken to ensure that the pedals were installed to 40 Nm prior to each testing session; however, it is possible that some human error may have been introduced as an analogue, rather than digital torque wrench was used. Due to the strain gauges in the P1 pedals measuring torque independent from the axle, they are unaffected by the torque setting on installation which provides an advantage of the P1 power system, especially if using across multiple bikes.

This study compared the P1 and V2 pedals to the Lode Excalibur Sport at a limited selection of power outputs, and although they were typical of those at which amateur cyclists train and race, the fact that a full range of power outputs was not compared is a limitation of this study. Previous studies (Gardner et al. 2004, Hopker et al. 2010) have used a dynamic calibration rig when assessing the validity of a power meter as this allows a full range of power outputs and cadences to be compared. Methods for applying a known force directly to the pedal using a dynamic calibration rig are not widely accessible and, therefore, not used.
with pedal-based systems (Novak and Dascombe 2016). Further investigation into the reliability and validity of the P1 and V2 pedals between 500–700 W is required and would provide athletes, coaches and researchers with valuable information prior to purchasing these power pedals.

6.5 Conclusion

The results of this study suggest that both the P1 and V2 pedals have acceptable test-retest reliability for amateur cyclists. With greater reliability observed for the P1 pedals, the results from this study will provide athletes, coaches and researchers with the confidence that these pedals could be used to monitor training adaptations during sub-maximal power outputs. The P1 pedals provided comparable data to the Lode Excalibur Sport at sub-maximal intensities with a mean difference of <2 W at power outputs between 100 and 250 W. In comparison, the V2 pedals significantly overestimated power output between 100 and 250 W, with a mean difference of 4–12 W. These results are important to athletes, coaches and researchers, especially if comparing team data or individual performances across different bikes and power systems. The P1 pedals provided slightly higher reliability than the V2 during sprint performance; however, both systems significantly overestimated power output, and some care should be taken when using these pedals to monitor sprint performance.

The results of this study have supported the use of the P1 pedals in the final study in this thesis with good test-retest reliability observed at power outputs <500 W. Despite these pedals appearing to significantly overestimate power output between 100 and 250 W, the mean difference of <2% is negligible from a practical perspective. Additionally, it is likely that the Mann Whitney-U test reported significant differences due to the limitations of the exported data from the Lode Excalibur Sport where no variation in power output is observed when tested in hyperbolic mode.
7 STUDY FOUR: THE RELIABILITY AND VALIDITY OF THE POWERTAP P1 PEDALS
BEFORE AND AFTER 100 HOURS OF USE

7.1 Introduction
Aspects of this chapter have been published in the International Journal of Sports Physiology and Performance (Wright et al. 2019). The results from experimental study three supported the use of the P1 pedals in the final study of this thesis; however, limited information about the reliability and validity of pedal-based power meters over an extended period was available. It has previously been suggested that reliability and validity studies on power measuring devices are limited to single testing sessions, with suggestions that reliability may be reduced for older systems (Zadow et al. 2018). To ensure that the results taken from the P1 pedals during the final study could be used with confidence, a short study was completed to compare the P1 pedals before and after 15 months of laboratory use.

Using a longitudinal repeated-measures study design, the aims of study four were to compare the test-retest reliability and concurrent validity of the P1 pedals before and after approximately 100 h of use. It was hypothesised that the reliability and validity of the P1 pedals would not be reduced after an extended period of laboratory use.

7.2 Methods
7.2.1 Participants
Initial testing (P1_{0}) was completed by ten male cyclists using a pair of new PowerTap P1 pedals (mean ± SD: age 34 ± 6 years, body mass 80.8 ± 8.8 kg, stature 1.83 ± 0.05 m). Following a period of 15 months and approximately 100 h of laboratory use, the testing protocol was repeated (P1_{100}) with a further ten male cyclists (mean ± SD: age 30 ± 7 years, body mass 80.9 ± 11.9 kg, stature 1.83 ± 0.08 m).
7.2.2 Experimental Procedures

During each testing period, the protocol was repeated on two occasions, separated by a minimum of 48 h. All testing was carried out on an electronically-braked cycle ergometer (Excalibur Sport, Lode, The Netherlands) with the pedals installed following the manufacturer’s guidelines. The experimental procedure was completed as detailed in study three, before and after a period of 15 months and approximately 100 h of laboratory-based testing.

7.2.3 Statistical Analyses

Shapiro-Wilk tests of normality made clear that data did not meet the assumption of normality ($P < 0.05$) resulting in non-parametric analyses. Comparisons between the Lode Excalibur Sport and the PowerTap P1 pedals were made using a Mann-Whitney-U test with agreement assessed using LoA. ES were calculated using Cohen’s $d$: trivial (<0.19), small (0.20–0.49), medium (0.50–0.79) and large (>0.80) (Cumming 2014). Test-retest reliability was measured using CV and TEM, and upper and lower 95% confidence limits. Statistical significance was set to $P = 0.05$, with all data reported as mean ± SD.

7.3 Results

A Mann-Whitney-U test identified significant differences between the Lode Excalibur Sport and the P1 pedals at 100 W (100 ± 0 W vs. 100 ± 2 W, $U = 100, z = -3.077, P = 0.006$), 150 W (150 ± 0 W vs. 151 ± 2 W, $U = 100, z = -2.969, P = 0.006$), 200 W (200 ± 0 W vs. 202 ± 3 W, $U = 80, z = -3.476, P = 0.001$), and 250 W (250 ± 0 W vs. 252 ± 2, $U = 100, z = -2.900, P = 0.006$).

Significant differences were also seen during the all-out sprints (964 ± 111 W vs. 1026 ± 116 W, $U = 498, z = -2.332, P = 0.020$, 95% LoA of $-62 ± 195$ W, ES = 0.55) (Figure 7.1c). No significant differences between the Lode Excalibur Sport and P1 pedals were observed during the
2-min all-out TT (403 ± 57 W vs. 399 ± 55 W, $U = 187$, $z = -0.365$, $P = 0.718$, 95% LoA of 4 ± 18 W, ES = 0.07) (Figure 7.1a).

Following approximately 100 h of use, a Mann-Whitney-U test showed no significant differences between the Lode Excalibur Sport and the P1₁₀₀ pedals at 100 W (100 ± 0 W vs. 100 ± 2 W, $U = 50$, $z = -4.393$, $P = 0.799$), 150 W (150 ± 0 W vs. 149 ± 2 W, $U = 40$, $z = -4.628$, $P = 0.183$), 200 W (200 ± 0 W vs. 199 ± 3 W, $U = 20$, $z = -5.208$, $P = 0.289$), and 250 W (250 ± 0 W vs. 249 ± 3 W, $U = 20$, $z = -5.205$, $P = 0.289$). Furthermore, no significant differences between the Lode Excalibur Sport and the P1₁₀₀ pedals were seen during the 2-min all-out TT (379 ± 45 W vs. 373 ± 40 W, $U = 190$, $z = -0.284$, $P = 0.583$, 95% LoA of 7 ± 16 W, ES = 0.16) (Figure 7.1b), or during the all-out sprints (979 ± 133 W vs. 936 ± 170 W, $U = 643$, $z = -0.821$, $P = 0.412$, 95% LoA of 43 ± 245 W, ES = 0.28) (Figure 7.1d).

Figure 7.1 Bland-Altman plots showing the limits of agreement between (a) the Lode Excalibur Sport and P1₀ peddles during a 2-min TT, (b) the Lode Excalibur Sport and P1₁₀₀ peddles during a 2-min TT, (c) the Lode Excalibur Sport and P1₀ peddles during a 10-s all-out sprint, and (d) the Lode Excalibur Sport and P1₁₀₀ peddles during a 10-s all-out sprint. The solid line represents the mean difference in power output, and the dashed lines represent the 95% limits of agreement.
The CV and TEM for the P10 pedals and P1100 during sub-maximal cycling bouts, the 2-min all-out TT, and all-out sprints can be found in Table 7.1.

Table 7.1 Coefficient of variation and absolute technical error of measurement between testing sessions 1 and 2, including 95% confidence limits.

<table>
<thead>
<tr>
<th>PowerTap P10</th>
<th>PowerTap P1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV ( % )</td>
<td>TEM (W)</td>
</tr>
<tr>
<td>100 W</td>
<td>0.6 (0.2–1.0)</td>
</tr>
<tr>
<td>150 W</td>
<td>0.7 (0.5–1.0)</td>
</tr>
<tr>
<td>200 W</td>
<td>0.7 (0.3–1.1)</td>
</tr>
<tr>
<td>250 W</td>
<td>0.6 (0.4–1.2)</td>
</tr>
<tr>
<td>2-min TT</td>
<td>1.3 (0.4–2.2)</td>
</tr>
<tr>
<td>All-out sprints</td>
<td>4.2 (1.8–6.7)</td>
</tr>
</tbody>
</table>

### 7.4 Discussion

The results of this study suggest that the PowerTap P1 pedals provide reliable data during sub-maximal cycling and that reliability is maintained after approximately 100 h of laboratory use. During all-out sprint performance, the P1 pedals appeared to overestimate power output by approximately 60 W when first tested and underestimate power output by approximately 40 W after prolonged use. The hypothesis that the reliability and validity of the P1 pedals would not be reduced after approximately 100 h of laboratory use has been accepted.

After approximately 100 h of laboratory use, the reliability of the P1 pedals was comparable to when initially testing during study three with a CV for P10 of 0.6–1.3% and 0.5–2.0% for P1100. The observed CV after prolonged use was also comparable to pedal based systems that were discussed in study three (Pallarés and Lillo-Bevia 2018). Based on the research by Hopkins et al. (2001), the CV in sports science reliability testing should not exceed 5%, and
in the present study the new and unused P1 pedals met this criterion for all tested power outputs; however, after a period of approximately 100 h of use, the CV observed during the all-out sprint performance increased slightly above this recommendation to 6.3%. It is suggested that some care should be taken when testing sprint performance with the P1 pedals, with power output overestimated during sprint performance when initial tested, and underestimated power output after prolonged use.

The results of the present study suggest that although not valid when initially purchased, the P1 pedals provide valid data after prolonged use when compared to the Lode Excalibur Sport. During the initial period of testing, a significant difference was seen for all power outputs between 100–250 W and in comparison, no significant differences were seen during repeat testing. The results of this study suggest that P1 pedals have acceptable test-retest reliability for amateur cyclists, which is maintained after prolonged use providing athletes, coaches and researchers with the confidence that the P1 pedals can be used to monitor training adaptations over an extended period.

7.5 Conclusion

The results of this study show that the P1 pedals measure within 2% of the Lode Excalibur Sport during sub-maximal power outputs. Additionally, this study demonstrated that the high reliability of the P1 pedals initially reported in experimental study three was maintained after prolonged use.
8 STUDY FIVE: A NOVEL ALL-OUT CYCLING PROTOCOL TO ESTIMATE CRITICAL POWER AND THE FINITE WORK CAPACITY

8.1 Introduction

Recent evidence has reported suggests that exercise at a power output equal to CP will not result in a physiological steady-state, with exhaustion occurring in 20–40 min (Carter et al. 2000, Brickley, Doust and Williams 2002, Dekerle et al. 2003). It has been suggested that CP can be used to set training zones (Jones et al. 2010), predict endurance performance (Black et al. 2014), and monitor adaptations to training (Gaesser and Wilson 1988). Despite the benefits of the CP being heavily documented in the scientific literature, the original CP protocol requires several testing sessions to calculate CP and Wʹ. When first introduced, the 3-min cycling test appeared to overcome this limitation of the original CP protocol and it was concluded that CP and Wʹ could be estimated from a single all-out testing session (Vanhatalo, Doust and Burnley 2007).

The results from experimental studies one and two raise some concerns about the validity of the 3-min cycling test. Firstly, experimental study one suggested that the testing mode can affect the calculation of CP, with results supporting the use of the isokinetic mode rather than the original protocol, which used a fixed resistance. These results were different to those previously reported within the literature, and it was assumed that the chosen cadence used in both protocols might have affected the results. It has previously been proposed that the cadence used to set the fixed resistance following the original 3-min protocol can affect the estimation of CP (Vanhatalo, Doust and Burnley 2008a). These findings were supported by the results of experimental study two, which suggested that higher cadences reduced EP, with a cadence of 10 rev·min⁻¹ above the participant’s self-selected preferred cadence, providing the best estimation of CP. Changes in cadence have also been demonstrated to
affect the estimation of CP when the 3-min cycling test is performed in isokinetic mode, with EP reduced by approximately 40 W when cycling at higher cadences (de Lucas et al. 2014). There is also evidence to suggest that training status of the participant can affect the calculation of EP, with CP significantly overestimated when using the 3-min cycling test with elite cyclists (McClave, LeBlanc and Hawkins 2011), and it has been suggested that the 3-min cycling test may need to be extended to account for participants with a larger \( W' \) (Karsten et al. 2014a). Finally, the 3-min cycling test relies on participants being highly motivated and capable of providing a maximal sprint effort throughout the entire test, which can be achieved by encouraging participants to maintain their highest possible cadence (Jones et al. 2010). Although steps are often taken to reduce the chances of pacing (e.g. removal of time-based feedback), it is difficult to say with certainty that this does not occur.

The findings from experimental studies one and two suggest that the 3-min cycling test is sensitive to several factors, including the testing ergometer, cadence selection and participant fitness. It is proposed that this protocol needs to be modified to reduce the sensitivity to such factors, ensuring that an all-out testing protocol can be used to estimate CP and \( W' \). The original theory underpinning the 3-min cycling test relies on the protocol being able to fully deplete \( W' \) within the first 150 s of the test and it is suggested that modifying the method at which \( W' \) is depleted could reduce the limitations of the original 3-min cycling protocol outlined above. Rather than using a sprint-based test, where the ergometer, pacing, and cadence selection may all affect the calculation of CP and \( W' \), it may be possible to deplete \( W' \) using a single TTE test within the severe exercise domain (e.g. 110% MAP). This suggestion would ensure that the duration of the test will change to suit each participant, resulting in \( W' \) being fully depleted. If the participant cycled at 110% MAP until muscular failure, it is reasonable to assume that \( W' \) would be depleted based on the same principle as the 3-min cycling test. If the participant was then immediately asked to cycle
maximally in isokinetic mode, it is proposed that the highest possible power output attained would equal CP. It has been demonstrated that the reconstitution of $W'$ occurs the moment power output falls below CP (Skiba et al. 2012) and, therefore, it is important to ensure that no rest occurs between muscular failure and the start of the all-out isokinetic effort. It is suggested that the isokinetic mode should be used based on the wider application of this mode over some of the alternative modes available on the Lode Excalibur Sport.

Using a repeated-measures study design, the aims of the final experimental study in this thesis were to 1) investigate the reliability and concurrent validity of a novel all-out cycling test to estimate CP and $W'$, and 2) investigate the physiological responses to cycling at CP calculated from the original protocol and the linear power-1/time mathematical model, 3-min cycling test and the novel all-out cycling test. It was hypothesised that 1) the novel all-out cycling test would provide a reliable and valid estimate of CP, 2) the novel all-out cycling test would provide a reliable and valid estimate of $W'$, 3) the 3-min cycling test would provide a valid estimation of CP, 4) the 3-min cycling test would significantly underestimate $W'$, and 5) CP calculated from the novel all-out cycling test would result in a power output that is sustainable for approximately 40 min.

8.2 Methods

8.2.1 Participants

Ten male cyclists (mean ± SD: age 33 ± 7 years, body mass 81.9 ± 10.1 kg, MAP 367 ± 43 W, $\dot{V}O_{2peak}$ 4.3 ± 0.5 L·min⁻¹) provided written informed consent to take part in this study and completed a PAR-Q. Each participant visited the laboratory on ten occasions with a minimum of 48 h between testing sessions. All testing was carried out on an electronically-braked cycle ergometer (Excalibur Sport, Lode, The Netherlands) with power output and cadence measured independently using power pedals (P1, PowerTap, USA). Heart rate (Edge 810,
Garmin, Switzerland) and breath-by-breath expired air (MasterScreen CPX, Viasys, Germany) were recorded throughout each testing session and exported at 5-s intervals. Prior to each testing session, a zero-offset calibration of the power pedals was completed.

The cadence monitor on the cycle ergometer was visible during all testing sessions with other forms of feedback (e.g. power output, elapsed time, heart rate) blinded from the participants. Strong verbal encouragement was provided during all testing sessions, and upon completion of each test, a capillary blood lactate sample was taken (C-Line, Biosen, Germany).

8.2.2 GET, MAP and \( \dot{V}O_{2\text{peak}} \) Protocols

During the first visit to the laboratory, a ramp test (20 W·min\(^{-1}\)) was completed to calculate GET, MAP and \( \dot{V}O_{2\text{peak}} \). Participants were instructed to cycle until volitional exhaustion and the test was terminated when cadence dropped by more than 10 rev·min\(^{-1}\) below the participant’s preferred cadence. After a period of rest, a familiarisation of the novel all-out cycling test was completed by each participant.

8.2.3 Original Critical Power Test

On separate days, each participant completed a TTE test to volitional exhaustion at 80, 100 and 105% MAP to calculate CP and \( W' \) (Karsten et al. 2014a). CP and \( W' \) were calculated using the linear power-1/time mathematical model.

8.2.4 3-min Cycling Test

Following a 10-min warm up at 100 W, participants completed a 3-min cycling test following the protocol described by Vanhatalo, Doust and Burnley (2007). The resistance during the test was set using the ergometer’s linear mode: linear factor = 50% \( \Delta / \text{cadence}^2 \). Based on the concerns raised in studies one and two regarding the method by which the participant’s preferred cadence was identified, the average cadence observed during the incremental
ramp test protocol was used for the calculation of the fixed resistance. Following 30 s of unloaded cycling, participants were encouraged to increase their cadence to approximately 110 rev-min⁻¹, 5 s before the start of the 3-min cycling test. Participants were then instructed to maintain the highest possible cadence for the duration of the 3-min cycling test. EP was calculated as the final 30 s average in power output (EP₃min), with WEP calculated as the power-time integral above EP (WEP₃min).

8.2.5 Novel All-out Cycling Test
Participants completed two novel tests on separate days to estimate CP and W′. The novel all-out cycling test was carried out in two continuous parts; the first was a TTE test performed at 110% MAP in the ergometer’s hyperbolic mode, with participants instructed to cycle until volitional exhaustion. Once cadence dropped below 10 rev-min⁻¹, the ergometer was switched to isokinetic mode, and the participants were then asked to cycle at their preferred cadence for a further 2 min, with maximal effort throughout. CP was estimated as the final 30-s average power output (EPNovel) observed during the isokinetic section, with W′ estimated as the power-time integral above CP observed during the 110% TTE (WEPNovel) (Figure 8.4).

8.2.6 Time-to-Exhaustion Test at Critical Power
The final three tests were completed to establish the metabolic responses to cycling at CP calculated from the original, 3-min and novel all-out testing protocols. If the power output at critical power from each testing protocol was within 1.5%, then the TTE test was not repeated on more than one occasion. Following a 10-min warm up at 100 W, participants were required to cycle at their calculated CP for 60 min, or until volitional exhaustion. Capillary blood lactate samples were taken at rest and 5-min intervals during each TTE test.

8.2.7 Statistical Analyses
Shapiro-Wilk tests of normality were performed on all data prior to analysis. Comparisons between CP with EP₃min and EPNovel, and between W′ with WEP₃min and WEPNovel were analysed
using a one-way repeated-measures ANOVA, LoA and Pearson’s product moment correlation coefficients. ES were also calculated using Cohen’s $d$, ranked as trivial (<0.19), small (0.20–0.49), medium (0.50–0.79) and large (>0.80) (Cumming 2014). SEE were used to measure the error associated with predicting EP and WEP from linear regression methods. The reliability of the novel all-out cycling test was measured using CV and ICC. All data are reported as mean ± SD with statistical significance accepted at $P < 0.05$.

8.3 Results

The Shapiro-Wilk test of normality showed that all data were normally distributed ($P > 0.05$).

Table 8.1 shows the mean $\dot{V}O_2$peak and peak blood lactate alongside the calculated CP/EP and $W'/WEP$ for each testing protocol. A mean $R^2$ value of 0.98 ± 0.03 was seen for the calculation of CP and $W'$ using the linear power-1/time mathematical model.

<table>
<thead>
<tr>
<th>Testing Protocol</th>
<th>$\dot{V}O_2$peak (L·min⁻¹)</th>
<th>Peak blood lactate (mmol·L⁻¹)</th>
<th>CP/EP (W)</th>
<th>$W'/WEP$ (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp test</td>
<td>4.3 ± 0.5</td>
<td>10.64 ± 1.93</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Original CP</td>
<td>4.1 ± 0.5</td>
<td>10.58 ± 1.80</td>
<td>271 ± 32</td>
<td>18.0 ± 5.0</td>
</tr>
<tr>
<td>3-min cycling test</td>
<td>4.1 ± 0.5</td>
<td>11.57 ± 1.83</td>
<td>281 ± 41</td>
<td>11.6 ± 2.8*</td>
</tr>
<tr>
<td>Novel all-out cycling test</td>
<td>4.3 ± 0.5</td>
<td>11.58 ± 2.31</td>
<td>279 ± 38</td>
<td>14.0 ± 2.5*</td>
</tr>
</tbody>
</table>

* Identifies significant differences from original CP protocol.

A one-way repeated measures ANOVA showed no significant difference between $EP_{3\text{min}}$ and CP (281 ± 41 W vs. 271 ± 32 W, $P = 0.354$, 95% LoA of 10 ± 37 W, ES = 0.27), or between $EP_{\text{Novel}}$ and CP (279 ± 38 W vs. 271 ± 32 W, $P = 0.293$, 95% LoA of 8 ± 27 W, ES = 0.23). Significant differences were seen between $WEP_{3\text{min}}$ and $W'$ (11.6 ± 2.8 kJ vs. 18.0 ± 5.0 kJ, $P = 0.015$, 95% LoA of −6.4 ± 10.5 kJ, ES = 1.47), and between $WEP_{\text{Novel}}$ and $W'$ (14.0 ± 2.5 kJ vs. 18.0 ± 5.0 kJ, $P = 0.021$, 95% LoA of −4.4 ± 7.9 kJ, ES = 0.92). Bland-Altman plots showing LoA between CP and $W'$ with their estimates are shown found in Figure 8.1.
A large correlation was observed between EP and CP for the 3-min cycling test (Figure 8.2a) and novel all-out cycling test (Figure 8.2b), and also between WEP and $W'$ for the novel all-out cycling test (Figure 8.2d). Comparable to the results of study two, a small correlation was observed between WEP and $W'$ for the 3-min cycling test (Figure 8.2c).

Table 8.2 shows the SEE between EP and CP, and between WEP and $W'$ for each all-out testing protocol, with a slightly lower result observed for the novel all-out cycling test. Additionally, the novel all-out cycling test demonstrated a larger correlation than the 3-min cycling test for both parameters.
Table 8.2 Standard error of estimates and Pearson’s product moment correlation coefficients between EP and CP, and between WEP and $W'$ observed during the 3-min cycling test and the novel all-out cycling test.

<table>
<thead>
<tr>
<th></th>
<th>3-min cycling test</th>
<th>Novel all-out test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r$</td>
<td>SEE</td>
</tr>
<tr>
<td>EP vs. CP</td>
<td>$0.88$, $P = 0.001$</td>
<td>16 W</td>
</tr>
<tr>
<td>WEP vs. $W'$</td>
<td>$0.05$, $P = 0.899$</td>
<td>2.2 kJ</td>
</tr>
</tbody>
</table>

Figure 8.2 Relationships between (a) EP$_{3\text{min}}$ and CP, (b) EP$_{\text{Novel}}$ and CP, (c) WEP$_{3\text{min}}$ and $W'$, and (d) WEP$_{\text{Novel}}$ and $W'$. The solid lines represent the mean bias, and the dashed lines represent the 95% limits of agreement.

Table 8.3 highlights the test-retest reliability of the novel all-out cycling test with a CV of 0.9% (EP) and 5.5% (WEP), with the ICC for EP and WEP being 0.99 and 0.86, respectively.

Table 8.3 Coefficient of variation and intraclass correlation coefficients between testing sessions for EP and WEP calculated during the novel all-out cycling test.

<table>
<thead>
<tr>
<th></th>
<th>CV (%)</th>
<th>ICC (α)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP$_{\text{Novel}}$ (1 vs. 2)</td>
<td>0.9</td>
<td>0.99</td>
</tr>
</tbody>
</table>

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Figure 8.3 and Figure 8.4 show the power profiles for both the 3-min and novel all-out cycling testing protocols. The power profile for the 3-min cycling test demonstrates a high initial power output, followed by a steady decline until a plateau (EP) is observed in the final 30 s. In contrast, the novel all-out cycling test consists of an initial period of constant-power output at 110\% MAP, followed by a maximal 2-min period of cycling in isokinetic mode. It should be highlighted that no rest was given between each testing phase of the novel all-out cycling test and a plateau (EP) was also observed in the final 30 s of this protocol.

![Figure 8.3](image-url)  
*Figure 8.3* Mean power output observed during the 3-min cycling test. The dashed lines represent the standard deviation.
The mean oxygen uptake during both testing protocols can be seen in Figure 8.5 and Figure 8.6. For both protocols, VO\textsubscript{2peak} was attained within the first 120 s, with 95% ramp test VO\textsubscript{2peak} observed during all tests. It should be noted that VO\textsubscript{2peak} did not show a decremental trend during the all-out testing protocols ensuring that the recommendations defined by Jones et al. (2010) were met.
Figure 8.6 Mean oxygen uptake observed during the novel all-out cycling test. The dashed lines represent the standard deviation.

It was found that CP calculated from all testing protocols resulted in a power output which was sustainable for less than 20 min, with a mean duration of 19 min 48 s observed from the original CP protocol, 16 min 22 s from the novel all-out cycling test protocol, and 15 min 25 s from the 3-min cycling test protocol (Table 8.4). It can also be seen from Figure 8.7 that the blood lactate and heart rate responses to each TTE test do not indicate steady-state exercise, while Figure 8.8 shows that oxygen uptake rose sharply but failed to reach the ramp test $\dot{V}O_2^{\text{peak}}$ at the point of exhaustion.

Table 8.4 Mean duration of each time-to-exhaustion test.

<table>
<thead>
<tr>
<th>Testing protocol</th>
<th>Time-to-exhaustion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original CP protocol</td>
<td>19 min 48 s</td>
</tr>
<tr>
<td>Novel all-out cycling test</td>
<td>16 min 22 s</td>
</tr>
<tr>
<td>3-min cycling test</td>
<td>15 min 25 s</td>
</tr>
</tbody>
</table>
The results of the present study found that EP\textsubscript{Novel} did not significantly differ and was within 8 W of CP, providing evidence to suggest that CP can be estimated from the novel all-out
testing protocol. Additionally, the results of this study highlight that some concerns remain about using an all-out cycling protocol to estimate $W'$, with $WEP_{\text{Novel}}$ and $WEP_{3\text{min}}$ both significantly underestimating this parameter when calculated using the original CP protocol. The novel all-out cycling test appears to provide excellent test-retest reliability for EP with a CV of 0.9% and an ICC of 0.99. In addition, this testing protocol demonstrated good test-retest reliability for WEP with a CV of 5.5% and an ICC of 0.86. Finally, with a non-steady-state response in blood lactate observed when cycling at CP, the results suggest that the original CP test, 3-min cycling test and novel all-out cycling test do not result in a CP that demarcates the boundary between the heavy and severe exercise intensity domains. The hypothesis that the novel all-out cycling test would provide a reliable and valid estimation of CP has been accepted. The hypotheses that the 3-min cycling test would provide a valid estimation of CP, but significantly underestimate $W'$, have also been accepted. The hypothesis that the novel all-out cycling test would provide a reliable and valid estimation of $W'$ has been rejected. Finally the hypothesis that CP estimated from the novel all-out cycling test would result in a power output that is sustainable for approximately 40 min, has been rejected.

The novel all-out cycling test demonstrated excellent test-retest reliability for EP with a CV of 0.9%, and although the CV for WEP was slightly above the acceptable 5% limit (5.5%) recommended by Hopkins (2000b), it was lower than the 7.9% reported by de Lucas et al. (2014) or the 20.7% reported by Johnson et al. (2011) when using the 3-min all-out cycling test. The novel all-out cycling test provided a closer estimation of $W'$ when compared to the 3-min all-out cycling test; however, it remained significantly lower than the original testing protocol (14.0 vs. 18.0 kJ). Jones et al. (2010) stated that tests shorter than 120 s should not be used during the calculation of CP due to concerns about mechanical power generation observed at higher power outputs. Despite the mean duration of the 110% TTE being 131 s,
it was noted that some participants reached exhaustion within 120 s and, therefore, it is
reasonable to suggest that this may have affected the calculation of WEP. Additionally, it is
noted that $W'$ was estimated as the power-time integral above CP during the 110% TTE
phase, based on the assumption that $W'$ would be depleted at the point of exhaustion. Figure
8.4 shows that some exercise is completed above CP during the isokinetic phase of the novel
all-out test, with suggestions that this unaccounted WEP could affect the estimation of $W'$.
The decision to not include this data in the calculation of WEP was based on the higher
variability of exported power output when testing in isokinetic mode and, as suggested, the
assumption that $W'$ would be depleted at the end of the 110% TTE phase. This is supported
by Chidnok et al. (2013), with suggestions that the total amount of work that can be
performed above CP is constant, irrespective of the type of exercise. For example, no
significant difference in $W'$ was observed during a ramp incremental test (13.2 kJ), a constant
work rate test (12.9 kJ), a 3-min cycling test (14.0 kJ), and a self-paced 3-min cycling test (12.8
kJ).

It has previously been demonstrated that EP and WEP calculated from the 3-min all-out test
will provide almost identical estimations of both CP and $W'$ (Vanhatalo, Doust and Burnley
2007). In the study by Vanhatalo, Doust and Burnley (2007), the authors found a near-perfect
relationship between CP and EP (289 W vs. 287 W), and between $W'$ and WEP (15.0 kJ vs.
15.4 kJ). In contrast, the results from the first experimental study of this thesis found that
the 3-min all-out cycling test significantly overestimated CP and underestimated $W'$, by
approximately 30 W and 9.0 kJ, respectively. In the present study, no significant differences
were observed between CP and EP (271 W vs. 281 W), and the estimation of $W'$ from the 3-
min all-out cycling test was significantly lower when compared to the original CP testing
protocol (18.0 kJ vs. 11.6 kJ), with no correlation observed ($r = 0.05, P = 0.899$). In agreement
with Bartram et al. (2017), these results suggest that it may not be possible to fully deplete
W’ from the 3-min all-out testing protocol. Although the recommendations for the calculation of a successful test from Jones et al. (2010) were met (e.g. no decline in VO₂), it is not possible to say with confidence if all participants in the current study maintained maximal effort throughout the testing protocol. The 3-min all-out testing protocol requires participants to be very motivated and it has been suggested by Bartram et al. (2017) that some conscious or unconscious pacing may occur during this testing protocol. It is therefore reasonable to suggest that the participants in this study did not maintain the highest possible cadence throughout the duration of the test, which would result in a lower than expected calculation of WEP. The novel all-out cycling protocol presented in this study still requires participants to be highly motivated; however, it is likely more feasible to maintain a high power output to failure (e.g. 110% MAP) than it is to maintain a maximal sprint for 3 min.

A recent study by Mattioni Maturana et al. (2018) found that the original CP protocol is affected by the mathematical model used and it was also recommended that at least one TTE test should last longer than 10 min. In the present study, an 80% MAP TTE test was included to elicit exhaustion within approximately 12 min; however, two participants were unable to cycle for 10 min during any of the three TTE tests. TTE tests at a percentage of MAP are often used within the literature; however, it is also possible to use time-based TT tests (e.g. 3, 7 and 12 min) (Karsten 2014b), to ensure that the above recommendations are met. Despite being able to control the duration when using TT tests to calculate CP, it has previously been suggested that TTE tests will result in a more accurate calculation of CP (Coakley et al. 2017), unless participants are fully accustomed to completing TT tests (Passfield and Coakley 2014).

A possible limitation of the present study is the use of the linear power-1/time mathematical model, with previous research suggesting that this may be prone to higher error than the 3-
parameter model (Bergstrom et al. 2014, Mattioni Maturana et al. 2018). The linear power
1/time model should not be dismissed, however, as it is still one of the most commonly used
mathematical models within the literature, and depending on the number and duration of
TTE used, has been demonstrated to accurately calculate CP and $W'$ (Mattioni Maturana et
al. 2018). It should also be noted that the study by Mattioni Maturana et al. (2018) did not
validate each model using a TTE test while cycling at the calculated CP, with conclusions
based on which model resulted in the best fit and lowest calculation of CP. Further research
is still required to determine the optimal mathematical model, number and duration of TTE
tests before conclusions are made about which combinations should be used as the “gold
standard” method for determining CP and $W'$.

To validate and understand the physiological responses to cycling at CP, a TTE was completed
at the power output associated with CP calculated from the original, 3-min and novel all-out
cycling testing protocols, with a mean TTE of 15–20 min observed. Figure 8.8 shows the mean
oxygen uptake observed during each TTE test, clearly demonstrating that ramp test $VO_2\text{peak}$
was not attained at the point of exhaustion. The results of the present study are in line with
previous studies (Brickley, Doust and Williams 2002, de Lucas et al. 2012), with
approximately 90% ramp test $VO_2\text{peak}$ observed at the point of exhaustion. This $VO_2$ response
is representative of exercise within the heavy exercise domain and it has been suggested
that power output needs to be increased by approximately 5% above CP for $VO_2\text{peak}$ to be
reached (de Lucas et al. 2012). In contrast, Figure 8.7 demonstrates that blood lactate
continued to rise during each TTE test, with post-test values above 8 mmol·L⁻¹, which may be
representative of exercise within the severe exercise intensity domain. If CP demarcates the
boundary between the heavy and severe exercise intensity boundaries, cycling at CP should
result in the highest power output at which blood lactate levels stabilise (Keir et al. 2015).
The results from the present study suggest that cycling at CP, irrespective of the protocol
used, results in a power output which is not sustainable for more than 20 min, with a non-
steady-state response in blood lactate observed. Similar results have been observed when
cycling at CP, with exhaustion occurring within 14 min (McClave, LeBlanc and Hawkins 2011),
22 min (de Lucas et al. 2012) and 20–40 min (Brickley, Doust and Williams 2002). The results
of the present study raise some questions about the validity of the CP concept and all-out
testing protocols at demarcating the boundary between the heavy and severe exercise
intensity domains.

This study has demonstrated that EP\textsubscript{Novel} is reliable and does not significantly differ from CP
calculated from the linear power-1/time mathematical model. Concerns remain about the
use of all-out testing protocols for estimating $W'$, and it is recommended that future research
attempts to fully understand the physiological basis of this parameter, especially during all-
out exercise. Finally, future research should focus on validating CP from all available
mathematical models.

8.5 Conclusion

The results from this study suggest that a novel all-out cycling protocol, which comprises of
a TTE test at 110% MAP, immediately followed by 2-min of maximal cycling in isokinetic
mode, provides a close estimation of CP. In line with previous all-out testing protocols,
caution should be exercised if using the novel all-out cycling protocol to estimate $W'$. Finally,
CP, irrespective of the method of calculation, may not represent the highest steady-state and
sustainable power output, with exhaustion occurring within 20 min when cycling at CP. To
the author's knowledge, this is the first study to directly compare EP calculated from the 3-
min cycling test to CP calculated from the original CP protocol and, subsequently, to
complete a CP validation test at both power outputs.
9 GENERAL DISCUSSION

9.1 Summary

The CP concept, which is defined by the nonlinear relationship between power output and the duration of tolerable exercise has been extensively researched since being introduced by Monod and Scherrer (1965). It has been suggested that the asymptote of this nonlinear relationship, CP, demarcates the boundary between the heavy and severe exercise intensity domains, with the finite amount of work available above CP, $W'$, calculated as the curvature constant (Monod and Scherrer 1965, Poole et al. 1988). The practical applications of the CP concept have been widely documented in the literature with suggestions that CP and $W'$ are sensitive to training (Gaesser and Wilson 1988, Jenkins and Quigley 1992), can be incorporated into a training programme to inform pacing strategy (Jones et al. 2010), and can also be used to highlight an athlete’s strengths and weaknesses (Hopker and Jobson 2012). Despite these benefits, the original CP testing protocol is not frequently utilised, with suggestions that athletes and coaches perceive it to be time-consuming and heavily reliant upon complex mathematics (Vanhatalo, Jones and Burnley 2011). Due to these concerns with the original CP testing protocol, it was suggested by Vanhatalo, Doust and Burnley (2007) that the parameters of the power-duration relationship could be estimated from a single 3-min cycling test.

The 3-min cycling test has received much attention since it was first introduced, with studies completing the testing protocol using a variety of ergometers and modified testing protocols (McClave, LeBlanc and Hawkins 2011, Bergstrom et al. 2012, Clark, Murray and Pettitt 2013, de Lucas et al. 2014, Karsten et al. 2014a, Dicks et al. 2016). Given the lack of consistency between the conclusions from these studies, and some authors raising concerns about the
validity of the 3-min cycling test protocol, the overall aim of this thesis was to develop a novel all-out cycling test to provide a reliable and valid estimate of CP and $W'$. 

The first study in this thesis was completed to investigate the reliability and validity of the 3-min cycling test when performed using two testing modes: a fixed resistance, and at a constant cadence. It was hypothesised that the 3-min cycling test would provide reliable and valid estimates of CP and $W'$ when performed in both testing modes. CP and $W'$ were initially calculated for each participant using the original CP protocol and linear power-1/time mathematical model. The participants were then asked to complete a 3-min cycling test against a fixed resistance following the testing protocol described by Vanhatalo, Doust and Burnley (2007). Additionally, the 3-min cycling test was completed at a constant cadence (i.e. isokinetic mode) following the protocol described by Karsten et al. (2014a). The key results of this study suggested that the 3-min cycling test provides a better estimation of CP when performed at a constant cadence, with CP significantly overestimated when completed at a fixed resistance. In support of previous studies, the results also suggested that the 3-min cycling test is not suitable for estimating $W'$, with a significantly lower estimate and poor reliability observed for both protocols (Dekerle et al. 2014, Vanhatalo, et al. 2008, Karsten et al. 2014a). The results of this study suggested that several factors may affect the estimates of CP and $W'$, including cadence selection, the duration of the protocol, participant fitness and pacing. With the results of this study not supporting those of previous studies with regards to the estimation of CP (Vanhatalo, Doust and Burnley 2007, Karsten et al. 2014a), questions were raised about the validity of the 3-min testing protocol.

Based on the findings of study one, the second study in this thesis focused on the cadence used to set the fixed resistance during the 3-min cycling test. It was suggested that this study may explain why the results of study one differed from the research of Vanhatalo, Doust and
Burnley (2007), and it was hypothesised that higher cadences would result in a reduction of EP. During study two, each participant was instructed to complete four all-out testing conditions with the fixed resistance set using the participant’s preferred cadence, their preferred cadence −5 rev·min⁻¹, preferred cadence +5 rev·min⁻¹, and preferred cadence + 10 rev·min⁻¹; the preferred cadence was self-selected by each participant before the start of the study. The results of this study suggested that EP is reduced upon the adoption of a higher cadence, with an increase of 10 rev·min⁻¹ above preferred cadence resulting in the closest estimation of CP, when compared to the original CP testing protocol. Upon further analysis, it was noted that the participants in this study naturally cycled at a cadence higher than their self-selected preferred cadence during the short and high-intensity TTE tests completed to calculate CP (e.g. 105% MAP). This observation suggested that the self-selected preferred cadence of each participant may not have been accurate, providing a possible explanation for why the 3-min cycling test appeared to overestimate CP in study one. The ambiguity of asking a participant to self-select a cadence, which is a critical parameter in setting the test’s fixed resistance, is a potential limitation of the 3-min cycling test, and the results of this study highlight that the method used for setting the fixed resistance needs careful consideration.

With the aim of minimising the potential limitations of the 3-min cycling test, it was proposed that the original protocol could be modified. During data analysis for the first two studies, it was noted that the Lode Excalibur Sport is unable to export the raw power output or torque data when tests are completed in hyperbolic mode, with the ergometer assuming that a natural variation in cadence does not affect power output. Additionally, it was noted that when switching between exercise modes (e.g. from hyperbolic to isokinetic mode), the raw data would include gaps of between 2 and 4 s at the point of switching modes. With a proposed modified protocol using the hyperbolic mode, immediately followed by the isokinetic mode, it was essential that these limitations of the Lode Excalibur Sport were
addressed. To overcome these limitations, it was decided that cycle-mounted power pedals could be used to export power output data during the evaluation of a novel CP protocol. At the time of starting study three, two of the most popular pedals, the PowerTap (P1) and Garmin Vector 2 (V2), had not been validated against a known “gold standard”. To have confidence in using a set of cycle-mounted power pedals to evaluate the novel protocol, the aims of study three were to 1) evaluate agreement between the P1 and V2 pedals and the Lode Excalibur Sport, and 2) investigate the reliability of the P1 and V2 pedals across a range of power outputs. The results of this study suggested that the P1 pedals have excellent test-retest reliability at sub-maximal power outputs. Additionally, the results suggested that the P1 pedals were more accurate than the V2 pedals when compared to the Lode Excalibur Sport at power outputs between 100 and 250 W.

The third study within this thesis supported the use of the P1 pedals to measure power output within the final study. It was acknowledged that the P1 pedals were recently purchased before testing, and questions were raised about how the reliability and validity may change over time. It is not unreasonable to assume that the reliability and validity of these pedals would be reduced after extensive testing and, therefore, a study was completed with the aim of investigating the reliability and validity of the P1 pedals before and after approximately 15 months and 100 h of laboratory use. The results of this study suggested that the P1 pedals provided valid data after 100 h of laboratory use, with the reliability of the pedals during sub-maximal cycling maintained.

Taking into consideration the results from the first two studies within this thesis, a novel all-out cycling test was developed with the aim of addressing some of the perceived limitations of the original 3-min cycling test. Firstly, questions were raised about the method for depleting $W'$ during the original 3-min cycling test, with concerns raised about pacing, and
the duration of the test. To overcome these potential limitations, it was suggested that \( W' \) could be fully depleted using a TTE test within the severe exercise intensity domain. At the point of exhaustion, it was hypothesised that if the participants continued to cycle maximally in isokinetic mode, the highest possible power output would be the same as CP calculated from the original linear power-1/time mathematical model. Concerns were also raised about the method used to set the fixed resistance during the 3-min cycling test, and the testing mode (i.e. linear mode), being unique to the Lode Excalibur Sport. It was suggested that the novel all-out cycling test would overcome these concerns by completing the test in hyperbolic and isokinetic modes, which are commonly available on laboratory-based ergometers and do not require a testing resistance to be selected.

The final study of this thesis investigated the reliability and validity of a novel all-out cycling test and compared the physiological responses to cycling at CP calculated from the original CP protocol, 3-min cycling test protocol, and a novel all-out testing protocol. The results suggested that the estimate of CP calculated from the novel all-out testing protocol was within 8 W of CP calculated from the original linear power-1/time mathematical model, with the estimate from the 3-min cycling test within 10 W. To validate CP calculated from each testing protocol, a TTE test was completed at the power associated with CP calculated from each testing protocol, with exhaustion occurring within 20 min, irrespective of the method of calculation. With the results of the final study suggesting that CP represents a power output that is sustainable for less than 20 min, these results raised some concerns about the practical application of CP and using the CP concept as the demarcation between the heavy and severe exercise intensity domains. This study concluded by suggesting that the “gold standard” method for calculating CP and \( W' \) needs to be established before further testing on all-out protocols is completed. With recent evidence demonstrating that CP and \( W' \) are affected by the number of testing sessions, the duration of TTE tests, and the mathematical
model used, the original testing protocol needs to be addressed to ensure that CP and, therefore, the demarcation between the heavy and severe exercise intensity domains is being accurately calculated.

9.2 All-out Testing Protocols

Despite initial evidence suggesting that the 3-min cycling test provides an almost identical estimation of CP when compared to the original CP protocol (Vanhatalo, Doust and Burnley 2007), some concerns have been raised about the validity of this testing protocol, especially with regards to the estimation of $W'$ (McClave, LeBlanc and Hawkins 2011, Karsten et al. 2014a). With an interest in estimating CP and $W'$ from a single all-out testing session, one of the primary aims of this thesis was to investigate the reliability and validity of the 3-min cycling test when performed using two protocols; the first was performed against a fixed resistance in line with Vanhatalo, Doust and Burnley (2007), and the second was performed at a fixed cadence (i.e. isokinetic mode) following the protocol used by Karsten et al. (2014a). The results of study one suggested that the 3-min cycling test significantly overestimates CP and underestimates $W'$ when using the protocol described by Vanhatalo, Doust and Burnley (2007). Furthermore, the results suggested that a better estimation of CP was observed when the testing protocol was completed in isokinetic mode. Based on the results of study one, the focus of this thesis changed to address some of the potential limitations of the 3-min cycling test, with the overall aim of modifying the protocol to provide a reliable and valid measure of CP and $W'$. Since the development of the 3-min cycling test by Burnley, Doust and Vanhatalo (2006), several modified protocols have been proposed with a focus on estimating CP and $W'$ from a single all-out testing session (Clark, Murray and Pettitt 2013, Black et al. 2014, Dekerle et al. 2014, Karsten et al. 2014a, Dicks et al. 2016). Typically, these studies have modified the testing protocol by completing it on different ergometers (e.g. SRM Ergometer), different modes of exercise (e.g. isokinetic), or by introducing a novel
method for determining the fixed resistance when completed using the Lode Excalibur Sport, as initially used by Burnley, Doust and Vanhatalo (2006).

The physiological underpinning of the 3-min cycling test relies on the complete depletion of \( W' \) during the initial 150 s of the testing protocol (Burnley, Doust and Vanhatalo 2006). Using the 2-parameter mathematical model as an example (\( P = W'/t + CP \)), it was suggested that if \( W' \) is reduced to zero, then any subsequent exercise must be fuelled by aerobic metabolism and, therefore, would equate to \( CP \) (Vanhatalo, Doust and Burnley 2007). Based on this theory, it was suggested that \( W' \) could be depleted using any available testing mode (e.g. fixed resistance or fixed cadence) (Karsten et al. 2014). The results presented in study one do not support this suggestion, with significant differences observed between EP and CP when completed against a fixed resistance, but no significant differences observed when completed at a fixed cadence. It is suggested that the 3-min cycling test is sensitive to the testing mode and, therefore, it may not be possible to compare the estimates of \( CP \) and \( W' \) when completed using different testing protocols.

One of the main limitations of the 3-min cycling test is the prerequisite ramp test to calculate GET and \( \dot{V}O_{2peak} \) data that is subsequently used to calculate the fixed resistance during the 3-min cycling test. Not only does this protocol require access to specialist equipment (e.g. a metabolic cart), it also means that the 3-min cycling test actually requires two testing sessions to complete. To overcome this limitation of the 3-min cycling test, several authors have suggested alternative testing protocols, with varying success. Firstly, it was suggested that the fixed resistance could be estimated using a percentage of body mass (Clark, Murray and Pettitt 2013), or by using a self-reported physical activity rating (Dicks et al. 2016). The results from these studies suggested that the 3-min cycling test could be completed without the need to calculate GET and \( \dot{V}O_{2peak} \); however, both methods rely on estimating the fixed
resistance, and without subsequent studies utilising these methods, it is difficult to state with certainty that either protocol can be used with confidence. Clark et al. (2016) investigated the possibility of completing the 3-min cycling test using a standard road bike and turbo trainer, with study participants required to self-select appropriate gearing. This protocol removed the need for a prerequisite test, but the authors did suggest that this protocol would not be suitable for novice cyclists as they may not be able to accurately select the most appropriate gearing throughout the test. The 3-min cycling test has also been investigated using isokinetic dynamometry, which uses a fixed cadence throughout the duration of the test. With the cadence pre-determined before the start of the test, completing the 3-min cycling test in isokinetic mode removes the requirement of the initial ramp incremental test to calculate GET and VO$_{2peak}$ and, subsequently, 50% $\Delta$ (Dekerle et al. 2014, Karsten, et al. 2014a).

Additionally, an isokinetic mode is frequently available on laboratory-based ergometers (e.g. Lode Excalibur Sport, SRM ergometer, Cyclus 2), which could allow the 3-min testing protocol to become more widely available in sports science laboratories. However, it has been suggested that the 3-min test does not provide a valid estimation of CP or $W'$, when completed in isokinetic mode using the SRM ergometer (Karsten, et al. 2014a). In contrast, the results from the first study of this thesis provided some support for completing the 3-min cycling test in isokinetic mode, with no significant difference observed between CP and EP. Despite these results, the wide LoA observed between the two measures (±29.7 W), and the significant differences observed between $W'$ and WEP, raised some concerns about completing the 3-min cycling test in isokinetic mode.

It has also been suggested that CP and $W'$ can be estimated by combining an incremental ramp test and 3-min cycling test into a single protocol (Constantini, Sabapathy and Cross 2014, Murgatroyd et al. 2014). Initially, these protocols are appealing as they would provide estimates of CP and $W'$, combined with GET and VO$_{2peak}$, from a single testing protocol;
however, some concerns about each study must first be addressed. The protocol used by Constantini, Sabapathy and Cross (2014), separated the incremental ramp test and 3-min cycling test by 20 min of active recovery. It is widely documented that the 3-min cycling test is highly demanding, leading to some concerns about the requirement of an athlete to complete this shortly after an incremental ramp protocol to exhaustion. Previous literature has also suggested that $W'$ may not be fully replenished after 30 min and, therefore, the rest period used in this protocol is likely to result in an underestimation of this parameter (Karsten et al. 2016). In the study by Murgatroyd et al. (2014), the fixed resistance was set by estimating $50\% \Delta$ as three times the participant’s body mass (kg) and using a standardised cadence of 80 rev·min$^{-1}$. The fixed resistance used within the 3-min cycling test is determined by both $50\% \Delta$ and cadence, and a fundamental concern with this approach is the estimation of $50\% \Delta$ given the sensitivity of the 3-min cycling test to changes in cadence, and consequently, changes in $50\% \Delta$ (Vanhatalo et al. 2008). Secondly, the second study within this thesis highlighted the importance of cadence selection when setting the fixed resistance and, therefore, caution should be exercised if using this protocol where a set cadence of 80 rev·min$^{-1}$ is used for all participants. The aim of the final study was to address the concerns raised above about the studies by Constantini, Sabapathy and Cross (2014) and Murgatroyd et al. (2014) by providing a single session testing protocol that can be used to estimate CP and $W'$. It is acknowledged that the novel all-out testing protocol included a period of cycling at 110% MAP, which would need to be calculated prior to the start of the test. It is anticipated, however, that any supramaximal power output could be used to deplete $W'$, which would result in a truly single-day testing protocol.

It has been demonstrated that the 3-min cycling test is sensitive to cadence variability, with EP reduced upon the adoption of higher cadences (Vanhatalo, Doust and Burnley 2008a). The effect of cadence selection has also been reported when the 3-min cycling test is
completed in isokinetic mode, allowing a direct comparison between different cadences (Dekerle et al. 2014). Furthermore, this observation has been highlighted when calculating CP and $W'$ from the original CP protocol, with suggestions that CP is reduced upon the adoption of higher cadences (60 vs. 100 rev-min⁻¹) (Hill et al. 1995). The primary explanation for these results is based on the suggestion that metabolic efficiency is increased at lower cadences (Hill et al. 1995), and is further supported by Abbiss et al. (2009) who suggested that lower cadences improve cycling economy. With cadence demonstrated to affect the parameters of the power-duration relationship, and their estimates calculated from the 3-min cycling test, it is surprising that a definitive method for establishing a participant’s ‘preferred’ cadence has not been identified. The method of asking a participant for their preferred cadence is problematic and highlighted in study two when comparing the self-selected preferred cadence of each participant to their mean cadence observed from each TTE test. It was observed that the participants naturally cycled at a higher cadence than those suggested at the beginning of the study during short, high-intensity TTE tests. This limitation was partially addressed in the final study where the cadence used to set the fixed resistance during the 3-min cycling test was selected as the mean cadence observed during the prerequisite incremental ramp test. In comparison to the results from study one, where EP was significantly higher than CP (~30 W), EP in the final study was not significantly different, and within 10 W of CP calculated from the linear power-1/time mathematical mode. It is suggested that the method for calculating the fixed resistance in the final study provides a plausible explanation for these results.

Recently, it has been reported in the literature that the original 3-min cycling test may be sensitive to some form of conscious or unconscious pacing (Bartram et al. 2017). It was explained by Jones et al. (2010) that a successful 3-min cycling test is reliant upon the athlete providing maximal effort throughout the test, and clear instructions should be given to
ensure that the test is not paced. It is difficult to say with certainty that an athlete does not pace the 3-min cycling test, with some subjective analysis of the exported data required upon completion. This is highlighted in Figure 9.1 where an example power profile from the 3-min cycling test is plotted for two different participants from study five. Both participants met the criteria defined by Jones et al. (2010), for example, 1) they were familiar with the testing protocol, 2) they were not provided with time-based feedback during the test, 3) no decrease in \( \dot{VO}_2 \) was observed during the test, and 4) at least 95% \( \dot{VO}_2^{peak} \) was observed when compared to the initial ramp test \( \dot{VO}_2^{peak} \) protocol. The concern with the data from participant one (solid circles), was the marked drop in power output within the first 20 s when compared to participant two. This rapid drop in power output is likely to directly affect the calculation in \( W' \) and may help to explain why this parameter is often significantly underestimated during the 3-min cycling test.

Figure 9.1 An example power profile during the 3-min cycling test from two participants. Solid circles = participant one, and open circles = participant two.

It is possible that the differences between the two participants highlighted in Figure 9.1 can be explained by the type of athlete they are, with a different power-duration relationship curve likely to be observed for TT riders compared to sprinters. Despite this suggestion, it is
possible that participant one did not give a maximal effort throughout the duration of the testing protocol, especially in the first 20 s; however, it was difficult to exclude this test from the data set when all other criteria for a successful test were met.

It was anticipated that the novel all-out cycling test would address the concern that some pacing may occur during the initial stages of the 3-min cycling test. Completing a maximal sprint to exhaustion without some form of pacing is not natural to cyclists, and not something that would be commonly included in a training programme. During data collection for this thesis, it was observed that the peak cadence during the 3-min cycling test was not as high as expected by some participants, and it was suggested that some participants may have cycled faster if the test was much shorter (e.g. 30 s). To overcome the possible limitation of pacing during the 3-min cycling test, it was proposed that the novel all-out cycling test used in study five would deplete $W'$ using a TTE test within the severe exercise intensity domain. TTE tests are frequently used during laboratory-based testing, and it is suggested that cyclists are more likely to be familiar with this concept than the ‘all-out’ sprint effort observed during the 3-min cycling test. Despite sprint intervals being regularly prescribed in training programmes (Allen and Coggan 2012), these are usually paced efforts, rather than starting at a maximal cadence. It has also been suggested that the 3-min cycling test may not be long enough to fully deplete $W'$ in all individuals, with a suggestion that a longer test may be required for those who have a larger $W'$ (Karsten et al. 2014a). It is not unreasonable to suggest that a single duration test may not be the most appropriate method for depleting $W'$ during an ‘all-out’ testing protocol.

It is suggested that the novel all-out cycling test builds upon the original 3-min cycling test protocol proposed by Burnley, Doust and Vanhatalo (2006) and Vanhatalo, Doust and Burnley (2007). Firstly, as stated above, it is anticipated that the novel all-out cycling test
reduces the impact of pacing that may occur within the initial stages of the 3-min cycling test. With $W'$ primarily depleted within the first 30 s of the 3-min cycling test, it is essential for a valid estimate of this parameter that pacing does not occur (Vanhatalo, Doust and Burnley 2007). Secondly, the protocol used in the novel all-out cycling test to deplete $W'$ ensures that the testing protocol is individualised for each participant as it has previously been suggested that the 3-min cycling test may not be long enough to fully deplete $W'$ in all participants (Karsten et al. 2014a). The novel all-out cycling test uses an open-ended period of cycling at 110% MAP to fully deplete $W'$ and, therefore, the duration of this period will vary depending on the individual. It is also suggested that the novel all-out cycling test could be completed in a single testing session, and despite the fact that a ramp incremental test was used to calculate 110% MAP, it is anticipated that any power output within the severe intensity domain could be used. Finally, it is suggested that the novel all-out testing protocol could be completed on a wider range of laboratory-based ergometers as the isokinetic mode is more common than the linear mode used in the 3-min cycling test.

A limitation of most ‘all-out’ testing studies is the omission of a CP validation test after the estimation of CP and $W'$, and it should be highlighted that the study by Vanhatalo, Doust and Burnley (2007) did not validate EP obtained from their 3-min cycling test. It is acknowledged that the original study by Burnley, Doust and Vanhatalo (2006) did complete a constant-power test, 15 W above and 15 W below EP for 30 min, or until exhaustion; however, without directly calculating CP in this study, some assumptions were made about the link between the two values. It should also be highlighted that the modified 3-min cycling tests mentioned above (Constantini, Sabapathy and Cross 2014, Clark et al. 2016, Dicks et al. 2016) did not include a CP validation test within their study designs, and despite these studies suggesting that modified single session testing protocols can provide valid measures of CP, some caution should be exercised when interpreting their data.
The final study in this thesis addressed this common limitation by completing a CP validation test for each protocol used: original CP test, 3-min all-out cycling test, and the novel all-out cycling test. This is, to the author’s knowledge, the first study to directly compare the 3-min cycling test to the original CP protocol and to subsequently perform a CP validation test for each protocol, providing an original contribution to the literature. The results of this study raised some questions about the validity of all CP testing protocols, with each resulting in a power output that was sustainable for less than 20 min. In support of completing a CP validation test at the calculated CP, it should be highlighted that in one of the original CP studies by Poole et al. (1988), participants were required to complete a validation test at CP and CP +5%, with a metabolic steady-state observed when cycling at CP. It is acknowledged, however, that recent studies have used a power output slightly above and below CP, with authors suggesting that this method identifies CP as range of approximately ±15 W. This is supported by Poole et al. (2016), who suggested that the typical error of measuring CP is approximately 5% and, therefore, providing a power output to the nearest Watt may not be the most appropriate method in an applied setting.

Based on the concerns above, Figure 9.2 provides a direct comparison between the testing protocols used within each experimental study of this thesis, and includes a range of 5% which could be used in a practical setting. For each testing protocol, EP has been presented as a percentage of the original CP calculated within each study. It is suggested that only the isokinetic protocol from study one, preferred cadence +10 rev·min\(^{-1}\) from study two, and the 3-min cycling test and novel all-out testing protocols from study five all result in an estimation within 5% of CP when calculated from the original testing protocol.
Figure 9.2 A comparison of CP estimates calculated during each experimental study. Each estimate is calculated as a percentage of the original CP observed within the respective studies. The dashed horizontal lines = CP ± 10%, and the dotted horizontal lines = CP ± 5%.

It has previously been suggested that the 3-min cycling test significantly underestimates $W'$ (Karsten et al. 2014a, Dekerle et al. 2014, Bartram et al. 2017), with these findings supported from the experimental studies within this thesis. In studies one, two and five, results suggested that the 3-min cycling test significantly underestimated $W'$ when compared to the original testing protocol. It was hypothesised that the novel all-out cycling test introduced in study five would provide a valid estimation of $W'$, due to the method at which $W'$ was depleted. It was assumed that by asking individuals to cycle until muscular failure would ensure that $W'$ was fully depleted based on the fact that the duration of the test would be individualised; however, the results suggested that $W'$ was also significantly underestimated using this protocol (14.0 ± 2.5 kJ vs. 18.0 ± 5.0 kJ). It is unclear why the 3-min cycling test or novel all-out cycling tests used within this thesis were unable to provide a valid estimate of $W'$. 
Questions are frequently raised about the true physiological underpinning of $W'$, and it is often reported within the literature that this parameter is inherently difficult to calculate (Dekerle et al. 2014). It was originally suggested by Monod and Scherrer (1965) that work completed above CP was derived from anaerobic sources; however, it is now widely accepted that this definition is overly simplified (Jones et al. 2010). A definitive definition of $W'$ remains elusive, and with this parameter being inherently difficult to calculate, some caution needs to be exercised when using the CP concept to inform training. Without an accurate calculation of both CP and $W'$, some of the practical applications of this model, for example the prediction of best performance times are questioned. It is suggested that the true physiological meaning of this parameter remains unclear and more work is required to fully understand this parameter before trying to estimate it from a single testing session.

9.3 Questioning the Critical Power Concept

It was originally suggested that CP represents the highest rate of aerobic metabolism that could be sustained without fatigue, allowing the demarcation between the heavy and severe exercise intensity domains (Monod and Scherrer 1965). In theory, CP allows a sports scientist or coach to determine the highest power output that a cyclist can maintain for an extended period, and the benefits of this information are evident for racing and participating in TT-based events. With the results of the final study suggesting that CP is sustainable for less than 20 min, and a steady rise in blood lactate observed, questions have been raised about the true definition of CP.

Following the seminal work of Monod and Scherrer (1965), several studies have attempted to understand the physiological responses to cycling at CP. Brickley, Doust and Williams (2002) instructed participants to cycle until exhaustion at CP with results suggesting that exhaustion will occur within 40 min. The authors suggested that cycling at CP does not result
in a sustainable power output and concluded by defining CP as a non-steady-state intensity that can be maintained for 20–40 min. The results of the study by Brickley, Doust and Williams (2002) are also supported by Carter and Dekerle (2014) who suggested that exhaustion occurred within 27 min when exercising at CP calculated from the linear power-1/time mathematical model. Jenkins and Quigley (1990) calculated CP from the linear work-time mathematical model, with results highlighting that 6 out of 8 participants were able to cycle at the power output associated with CP for 30 min. In contrast, McLellan and Cheung (1992) reported that only 1 of the 14 participants were able to complete 30 min of cycling at CP. These results are further supported by the results of study five where CP was calculated from the linear power-1/time mathematical model, the 3-min cycling test, and a novel all-out cycling test.

The results of study five suggested that CP, irrespective of the method of calculation, resulted in a power output that was sustainable for less than 20 min, with a mean duration of 19 min 48 s observed from the original CP protocol, 16 min 22 s from the novel all-out cycling test, and 15 min 25 s from the 3-min cycling test. It is possible that participant fitness may explain these results, with a suggestion that highly trained athletes will be more accustomed to cycling at power outputs at the limit of their metabolic steady-state. It was noted that the participants in the study by Jenkins and Quigley (1990), where the majority were able to cycle at CP for 30 min, had a VO\textsubscript{2max} of approximately 74 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}. In contrast, the participants in study five had a VO\textsubscript{2max} similar to those in the study by McLellan and Cheung (1992) (\textasciitilde52 ml·kg\textsuperscript{-1}·min\textsuperscript{-1} vs. \textasciitilde54 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}), and in both studies, participants were on average, unable to cycle at CP for more than 20 min.

The MLSS is regarded as the “gold standard” test for establishing the highest exercise intensity which will result in a steady-state production of blood lactate (Kilding and Jones...
2005). It has previously been reported that elite endurance cyclists can sustain the power associated with MLSS for 1 h, with a mean blood lactate of 7.4 ± 2.5 mmol·L⁻¹ (Hoogeveen, Hoogsteen and Schep 1997) and, therefore, it has been suggested that the MLSS provides a verification of the maximal metabolic steady-state (Iannetta et al. 2018). Considering the suggestions that CP demarcates the boundary between the heavy and severe exercise intensity domains, and that it has been defined as the power associated with the highest rate of aerobic metabolism, it is reasonable to assume that CP and MLSS will occur at similar power outputs. Several studies have directly compared CP to MLSS, with results suggesting that CP occurs at a significantly higher power output. Caritá et al. (2009) reported that although CP and MLSS were highly correlated, CP overestimated MLSS by approximately 30 W in well-trained cyclists. These results are supported by Pringle and Jones (2002), and Dekerle et al. (2003), who both found that CP overestimated MLSS in cyclists by approximately 20 W and 30 W, respectively.

More recently, CP calculated from the nonlinear 2-parameter mathematical model and the 3-min cycling test were compared to the power output associated with MLSS and, in support of previous literature, CP from both testing protocols was found to overestimate MLSS by approximately 20 W (Mattioni Maturana et al. 2016). The authors concluded that a standardised testing protocol for determining CP is still required, whilst questioning the true physiological basis of CP. With CP consistently occurring at a significantly higher power output to MLSS, it is difficult to see how the two measures are physiologically equivalent. Furthermore, CP appears to be tolerable for 20–40 min, which would not be expected of a power output associated with a metabolic steady-state (Brickley, Doust and Williams 2002). The physiological responses to cycling at CP reported in study five support previous literature (Brickley, Doust and Williams 2002, Carter and Dekerle 2014), raising questions about the true definition of CP. Together with the evidence suggesting that CP consistently
overestimates MLSS, concerns about the practical application of the CP testing protocol are
evident. Previous literature has supported the use of CP by coaches as it provides reliable
test-retest data (Triska et al. 2017), can be used to predict performance (Black et al. 2014),
is sensitive to training (Jenkins and Quigley 1992), and requires limited specialist equipment;
however, the concerns raised above would suggest that if CP is used to inform training, then
this may lead to overtraining.

The studies outlined in this section have raised questions about the accuracy of the CP
concept in demarcating the boundary between the heavy and severe exercise intensity
domains. With the CP concept based on a mathematical foundation, this leads to several vital
assumptions about the human body, and it is possible that these may go some way to explain
why CP calculated within study five appeared to overestimate a metabolic steady-state.
Firstly, it is assumed that the production of energy is reliant upon the anaerobic and aerobic
systems, with both compartmentalised (Jones et al. 2010). This is an overly simplistic
approach to energy production and leaves the CP concept open to criticism and potential
measurement error (Clarke and Skiba 2013). Secondly, it is suggested that the asymptote of
the power-duration relationship, CP, is sustainable indefinitely, despite our knowledge that
this is not true. Given enough time, power output will decrease due to other physiological
factors that affect exercise tolerance (e.g. glycogen depletion) (Jeukendrup 2011). A
fundamental assumption of the CP concept is that there is no limit to the maximum
instantaneous power output that can be achieved by an individual. To overcome this
assumption, Morton (1996), introduced the nonlinear 3-parameter mathematical model
which included the additional parameter, k. This additional parameter allowed a free-floating
x-axis asymptote, which is invariably negative, resulting in a maximum instantaneous power
\( P_{\text{max}} \) that can be used during analysis. Despite some authors (Mattioni Maturana et al. 2016)
suggesting that the 3-parameter nonlinear mathematical model should be used as the
criterion method for calculating CP and $W'$, it is less commonly used in the literature. This is possibly due to the perceived mathematical complexity of this model, or the minimum requirement of four TTE tests. Finally, that exhaustion occurs when $W'$ is fully depleted has been questioned, with Morton (1996) suggesting that if the power output during a TTE test was reduced slightly at the point of exhaustion, but still above CP, the cyclist would be able to continue, even if for a short duration. With the aim of providing more confidence in using the CP concept in a practical setting, it is suggested that further research is required to address the assumptions raised above.

Throughout this thesis, it has been proposed that the physiological responses to exercise can be categorised into four exercise intensity domains: moderate, heavy, severe and extreme (Poole 2009). There is some confusion within the literature with authors using the terms very heavy and severe in replacement for severe and extreme (Whipp 1996). Despite these differences, the physiology responses remain the same irrespective of the terminology used. For example, some authors (Keir et al. 2015) would suggest that CP demarcates the boundary between the heavy and very heavy exercise intensity domains, rather than the heavy and severe domains as more commonly reported in the literature (Poole 2009). Research based on swimming has suggested that a fifth exercise intensity domain, termed ‘very heavy’ should be used to separate the heavy and severe exercise intensity domains (Toubekis and Tokmakidis 2013). Figure 9.3 highlights how the introduction of the very heavy exercise intensity domains can be used to differentiate CP from MLSS, providing separate physiological responses to identify the boundaries between each domain.
The exercise intensity domains outlined by Toubekis and Tokmakidis (2013) would suggest that CP does not represent a power output where a steady-state response in blood lactate or VO\(_2\) are observed. This suggestion is further supported by the results of the final study in this thesis where a progressive increase in blood lactate was observed without the attainment of VO\(_2\)\(_{\text{max}}\). Limited research has focused on the ‘very heavy’ exercise intensity domain, and current literature continues to use the four exercise intensity domains used throughout this thesis (Burnley et al. 2016). There is growing evidence to suggest that CP does not demarcate the heavy and severe exercise intensity domains as initially proposed, and it is suggested that more research focusses on using the ‘very heavy’ exercise intensity domain to provide a clearer definition of CP.

9.4 General Limitations

Throughout this thesis, CP and W’ were calculated following the original methods described by Monod and Scherrer (1965) and the linear power-1/time mathematical model, supporting previous literature that had focused on the 3-min cycling test (Burnley, Doust and Vanhatalo...
2006, Vanhatalo, Doust and Burnley 2007, Dekerle et al. 2014, Karsten et al. 2014a). It has recently been suggested that the linear power-1/time mathematical model may overestimate CP, depending on the number and duration of each TTE test used within the calculation (Mattioni Maturana et al. 2018); however, it has been suggested that CP and \( W' \) can be accurately calculated using two or three TTE tests if two of these last between 10 and 20 min (Mattioni Maturana et al. 2018). With the aim of improving the confidence of calculating CP, some authors include extra TTE tests if the observed standard error (SE) is > \( \pm 3 \) W (Ferguson et al. 2007). Additionally, it is now common to utilise the best (BIF) and worst individual fits (WIF) when selecting the mathematical model used to calculate CP and \( W' \).

During this approach, CP and \( W' \) are calculated using all available mathematical models, and the model producing the BIF for each participant is used for all subsequent analyses (Black et al. 2016).

Following the completion of study five, it was noted that some participants reached exhaustion for two of the TTE tests in less than 7 min and it is not unreasonable to suggest that for some participants, an accurate calculation of CP and \( W' \) was not obtained. Despite this observation, it should be noted that the mean \( R^2 \) for experimental studies one, two and five was 0.98 \( \pm 0.03 \) suggesting that the model used for all studies resulted in a good mathematical fit. Finally, it is generally recommended to use 4–8 TTE test when calculating CP and \( W' \) (Gaesser and Wilson 1988, Poole et al. 1988, Housh, Housh and Bauge 1989, Mattioni Maturana et al. 2018); however, this is not always possible when calculating these parameters as part of a large study design. For example, participants in studies one, two and five completed 8–10 tests on separate days requiring a high level of motivation and commitment to each study. The decision to use three TTE tests to calculate CP and \( W' \) was based on previous research that has used three TTE tests, along with the concerns of including additional testing sessions on top of an already demanding testing protocol.
The omission of a CP validation test in studies one and two was recognised and, therefore, such a test was included in the final study. Without observing the physiological responses to exercise at the calculated CP, it is difficult to make conclusions about the validity of all-out testing protocols in the estimation of CP and $W'$. With CP described as demarcating the boundary between the heavy and severe exercise intensity domains, a CP validation test should be used to observe the responses in VO$_2$ and blood lactate whilst exercising at the calculated CP. Based on the limitations described above, and study five suggesting that CP is sustainable for less than 20 min, it is possible that the linear power-1/time mathematical model may have overestimated CP in studies one, two and five. To examine these concerns, the data collected from study five was retrospectively analysed to calculate CP from the nonlinear 2-parameter mathematical model (Table 9.1). Comparable to current literature (Bergstrom et al. 2014, Mattioni Maturana et al. 2018), a reduction in CP, and an increase in $W'$ was observed when using the nonlinear 2-parameter mathematical model, and it is not unreasonable to assume that CP may be further reduced if using the nonlinear 3-parameter mathematical model. With only three TTE tests available to calculate CP and $W'$, it was not possible to include data for this model and it is suggested that additional research is required to compare the physiological responses to cycling at CP when calculated using all available mathematical models.

**Table 9.1 Comparison of mathematical models observed during study five.**

<table>
<thead>
<tr>
<th>Mathematical Model</th>
<th>CP (W)</th>
<th>$W'$ (kJ)</th>
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<tbody>
<tr>
<td>Nonlinear 2-parameter</td>
<td>267 ± 32</td>
<td>19.6 ± 5.1</td>
</tr>
<tr>
<td>Linear power-1/time</td>
<td>271 ± 32</td>
<td>18.4 ± 4.8</td>
</tr>
<tr>
<td>3-min cycling test</td>
<td>281 ± 41</td>
<td>11.6 ± 2.8</td>
</tr>
<tr>
<td>Novel all-out cycling test</td>
<td>279 ± 38</td>
<td>14.0 ± 2.5</td>
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9.5 Recommendations for Future Research

This thesis focused on the reliability and validity of all-out testing sessions to estimate CP and $W'$, and concerns about the 3-min cycling testing protocol led to the development of a novel all-out testing protocol. The results from study five suggested that CP could be estimated from an all-out testing protocol, with a closer estimation of CP found from the novel all-out testing protocol when compared to the 3-min cycling test. Following a CP validation test for the original CP test, the 3-min cycling test, and the novel all-out test, it was suggested that the power output associated with CP was not sustainable for longer than 20 min. This thesis demonstrates some potential to use all-out testing protocols to estimate CP; however, it also raises a question about the fundamental basis of the CP concept. Based on these concerns, the following recommendations are made for future research.

Firstly, and most importantly, a valid protocol to calculate CP and $W'$ using the power-duration relationship needs to be established. This is due to recent evidence suggesting that both parameters are affected by several factors, including the mathematical model, and the number and duration of TTE tests used during calculation (Mattioni Maturana et al. 2018). Based on these suggestions, it is essential that CP calculated from each mathematical model outlined by Mattioni Maturana et al. (2018) are validated to ensure that future studies use a "gold standard" protocol.

During the last ten years, several all-out testing protocols have been developed with the aim of providing the most reliable and valid estimation of CP and $W'$. Typically, research studies have focused on the testing population, ergometer, testing mode, duration, and specific testing parameters (e.g. cadence). It is suggested that future all-out testing protocols are completed in the field with a focus on the ecological validity of field-based assessment. With power measurement widely available to athletes and coaches, recent research has focused
on field-based testing protocols (Karsten et al. 2014b, Triska et al. 2015). It is suggested that laboratory-based testing is often used to inform training and race strategy and, therefore, it is imperative that the data collected in the laboratory is transferable to the field. With the measurement of power output known to differ between systems (e.g. laboratory-based ergometer and training bike), completing field-based assessment using the athlete’s own bike and power meter appears to be the logical solution. Despite evidence that the novel all-out test presented in the final study may provide a valid estimation of CP, it is not possible from the results of this study to fully understand how these data may compare to field-based measures.

It is also suggested that more research is required on the method used to determine an individual’s preferred cadence if using the original 3-min cycling test protocol. The validity of the 3-min cycling testing protocol has been questioned throughout this thesis with results suggesting that the cadence used to set the fixed resistance affects the estimation of CP. It is essential for future research using this protocol that the participant's personal choices cannot affect the testing results. Research by Clark, Murray and Pettitt (2013) and Dicks et al. (2016) go some way to address this concern, but their methods are prone to human error with the fixed resistance still requiring some estimations from the participant and researcher.

More research is required to gain a deeper understanding of the role of $W'$ in all-out testing protocols. The results of each study within this thesis would suggest that all-out testing protocols should not be used to estimate $W'$, with results consistently demonstrating that WEP significantly underestimates $W'$. The physiological basis of all-out testing assumes that the highest possible power output after $W'$ is fully depleted will be equivalent to CP. With concerns raised about the validity of all-out testing protocols at estimating $W'$, it is
reasonable to assume that this would result in an overestimation of CP. It has previously been suggested that the CP concept can be used to predict the highest power output possible for a given duration; however, this relies on a valid calculation of both CP and $W'$. It is, therefore, essential that both parameters can be calculated accurately from all-out testing protocols if they are to be used in an applied setting.

Research focusing on swimming performance has suggested that CP may represent the boundary between the very heavy and severe exercise intensity domains (Toubekis and Tokmakidis 2013). With limited research focusing on the very heavy exercise intensity domain, it is suggested that future research should focus on the unique physiological responses to exercising within this domain. It is suggested that the demarcation between the very heavy and severe exercise intensity domains may help to differentiate CP and MLSS.

Sports science research often uses only male participants, limiting its application in an applied setting. To avoid any unknown confounding effects of sex differences on the calculation of CP and $W'$, only male participants were used in the experimental studies of this thesis. It is suggested that future CP research should focus on female participants to gain a wider understanding of the CP concept.

Finally, it is recommended that irrespective of the protocol used for calculating CP, a validation test is completed to ensure that a metabolic steady-state is observed when cycling at the power output associated with CP. It is essential that researchers focus on what CP truly represents, and how this parameter can be used in an applied setting.
9.6 Practical Applications

The results of this thesis suggest that further research is required before the calculations of CP and \( W' \) can be used with confidence, and several recommendations have been provided in section 9.5. If these concerns are addressed, and a valid method for calculating CP and \( W' \) is established, the following practical applications are suggested.

Firstly, CP can be used by coaches to set power-based training zones, and to monitor changes in performance throughout the season. It has been stated throughout this thesis that the use of CP by coaches is limited due to the perceived complexity of calculation and the time it takes to complete the original testing protocol. If it can be demonstrated that CP can be estimated from a single all-out testing protocol, this may provide an attractive alternative to the original protocol.

Secondly, the mathematical basis of the CP concept allows the prediction of the highest power output for any given duration, which could be beneficial during TT races; however, this relies on an accurate calculation of both CP and \( W' \). With previous studies generally suggesting that all-out testing protocols underestimate \( W' \), it may be some time before this could be used in the field.

Finally, the 3-min and novel all-out testing protocols demonstrated high test-retest reliability throughout this thesis for the estimation of CP. These results provide confidence for the use of all-out testing protocols for testing the effectiveness of training interventions, or intervention-based studies where a short, but reliable, physiological testing protocol is beneficial.
9.7 Final Conclusions

The results of this thesis suggest that all-out testing protocols are reliable and that they provide a close estimation of CP when calculated from the power-1/time mathematical model. The 3-min cycling test is sensitive to both the testing mode and cadence raising some concerns about this protocol. A novel all-out testing protocol has been introduced to overcome some of the concerns associated with the 3-min cycling test, and initial findings suggest that this protocol provides a reliable and close estimation of CP. The final study in this thesis raised questions about the validity of the “gold standard” testing protocol used to calculate CP and $W'$, with participants unable to cycle for longer than 20 min at the power associated with CP. Before further conclusions are made about the validity of all-out testing protocols, it is essential that the original testing protocol is validated to ensure that CP and $W'$ provides an accurate demarcation of the boundary between the heavy and severe exercise intensity domains.
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APPENDIX A – PEER REVIEWED PUBLICATIONS

A.1 International Journal of Sports Medicine

The Reliability and Validity of the 3-min All-out Cycling Critical Power Test

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Key words
exercise testing, anaerobic capacity, training science, isokinetic

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Abstract
Research suggests that critical power (CP) can be estimated from a single 3-min bout of all-out cycling. The purpose of this study was to investigate the reliability and validity of the 3-min all-out cycling test when carried out at a constant cadence (isokinetic) and against a fixed resistance (isometric). 12 participants completed 8 tests: 1) a ramp test, 2–4) 3 fixed power tests to calculate CP and W using the 1/4 line mathematical model, and 5–8) four 3-min all-out tests to calculate CP and W using 2 isokinetic and 2 isometric tests. There was no significant difference between CP-isokinetic and CP (P = 0.377). There were significant differences between CP-isokinetic and CP (P < 0.001) and W-isokinetic and W (P < 0.001). The coefficient of variation in CP-isokinetic, CP-isometric and W-isokinetic and W was 1.03, 1.17, 1.44 and 9.30%, respectively. The 3-min all-out isokinetic test provides a reliable estimate of CP and a valid estimate of CP. The 3-min all-out isometric test provides a reliable estimate of CP but not a valid estimate of CP. Furthermore, these results suggest that the 3-min all-out test should not be used to estimate W.

Introduction
Athletes frequently use laboratory exercise testing to assist with training design and race strategy [12, 24]. There are numerous testing protocols available when monitoring the physiological condition of an athlete, including lactate threshold (LT), maximal lactate steady state (MLSS) and maximal oxygen uptake (VO₂max) protocols. In comparison to LT, MLSS and VO₂max, Critical Power (CP) testing can provide athletes with information about both the anaerobic and aerobic energy systems [16]. CP has been defined as the highest sustainable rate of aerobic metabolism [15], providing an estimate of the heavy-skeletal exercise domain boundary [26]. Jones et al. [22] stated that CP is rate but not capacity limited. They also suggested that there is an anaerobic component (finite work capacity), which is capacity- but not rate limited, and it is defined as the amount of work that can be completed above CP (W). Johnson et al. [21] recommended the use of CP testing when monitoring power adaptations to training but, although the benefits of CP testing are known, the original testing protocol is time consuming. Traditionally, the protocol involves completion of 3–8 time-to-exhaustion tests, each performed on separate days [7, 13, 17, 18, 20, 25]. Due to the time-consuming nature of multi-day testing protocols, researchers have recently focused on single-day testing protocols [26]. In 2006, Brackley et al. [5] investigated the possibility of estimating VO₂peak and critical power from a 30-s all-out test. This was based on the assumption that W is finite and, if fully depleted, would result in a power output being maintained from only aerobic metabolism and therefore equal to CP. The results of this study suggested that a longer test was required to elicit a power output that corresponds to CP leading to the development of the 3-min all-out cycling test [6]. Burnham et al. [6] concluded that the 3-min test could be used to establish VO₂peak and MLSS, which may prove to be beneficial over traditional multi-day testing protocols. Further studies have suggested that CP and W can be estimated from the 3-min all-out cycling test [25] and that this test provides a reliable estimate of CP. The estimates of CP and W were conse-
quently designated end power (EP) and work above end power (WEP), respectively [26].

The 3-min all-out test was originally carried out using the Lode Excalibur Sport cycle ergometer, utilizing a fixed resistance (linear mode). This fixed resistance was set using the following equation: linear factor (resistance) = power output/maximum grade, where power output is determined as the midway point between gas exchange threshold (GET) and VO_{peak} [28]. With the linear mode being unique to the Lode Excalibur Sport, this provides a potential limitation of the original testing protocol, unless it can be established that the 3-min all-out test can also be carried out on other cycle ergometers. Several studies have investigated the reliability and validity of the 3-min all-out test using alternative cycle ergometers and testing modes, including, for example, the Monark ergometer, Computrainer and SRM ergometer in isokinetic mode [3, 18, 23]. Due to the physiological basis of the original test, Karsten et al. [18] argued that an agreement between the EP observed during the 3-min all-out test and CP from original methods, each participant took part in tests, each separated by a maximum of the mode of measurement. However, Karsten et al. [18] found that, while providing a reliable estimate of CP, the SRM ergometer set in isokinetic mode underestimated CP by approximately 35 W. The results of this study also suggested that the isokinetic mode does not provide a reliable or valid estimate of CP. Dekker et al. [10] compared CP to EP using the SRM ergometer in isokinetic mode performed at 60 and 100 rev·min⁻¹ and, although no significant differences were found, the results suggested that EP overestimates CP. Although WEP did not differ from CP, Dekker et al. [10] suggested that care should be taken when using this protocol as it also provided poor reliability. Due to the low levels of agreement, the authors suggested CP may not truly represent CP. In contrast, Tsi [27] reported that the 3-min all-out test in isokinetic mode using the Lode Excalibur Sport cycle ergometer underestimated CP by approximately 4%. Although it has been suggested that the 3-min all-out cycling test can estimate CP and W′ against a fixed resistance using the Lode Excalibur Sport, research is less clear when using isokinetic ergometry [10, 18, 27].

The aim of the present study was to investigate the reliability and validity of the 3-min all-out test in determining critical power and W′ when performed at a constant cadence (isokinetic mode) and when using a fixed resistance (linear mode). It was hypothesized that both the isokinetic and linear modes would provide a reliable and valid estimate of CP and W′.

**Methods**

**Participants**

12 male cyclists (mean ± SD: age 32 ± 0.6 years, body mass 81.0 ± 6.6 kg, Maximum Aerobic Power (MAP) 249 ± 30 W, VO_{peak} 4.4 ± 0.51 l·min⁻¹) provided written informed consent to participate in the study. The study was conducted in accordance with the ethical standards of the international Journal of Sports Medicine [14] and was approved by the host university’s ethics committee. Each participant performed two 1-h tests, each separated by a 48-h rest period. Test 1 was carried out in order to calculate gas exchange threshold (GET), MAP and VO_{peak} along with providing each participant with a familiarization trial of the 3-min all-out cycling test. The remaining 7 tests were carried out to calculate CP and W′ and the estimates CP and WEP. All testing was carried out using an electronically braked cycle ergometer (Excalibur Sport, Lode, The Netherlands). The bike settings for each participant (e.g. seat and bar height) were noted on the first visit to allow replication during all tests. The participants were instructed to avoid heavy exercise in the 24 h prior to each testing session, to avoid food intake for 3 h prior to testing and to drink 500 ml of water 2 h before arriving at the laboratory. Following the measurement of GET, MAP and VO_{peak}, subsequent tests were carried out in a randomized order. During all testing sessions, strong verbal encouragement was provided; however, no feedback was given regarding elapsed time or power output.

**GET, MAP and VO_{peak} protocol**

Participants completed an incremental exhaustive ramp test to determine GET, MAP and VO_{peak}. Participants started at a work rate of 150 W with 20 W increments at the highest possible cadence. Breath-by-breath expired air (Oxycon Pro, Viasys, Germany) and heart rate (ECG, Polar, Finland) were recorded throughout the test with a post-test capillary blood lactate sample (Lactate Pro, Arkray, UK) taken immediately after completion of each test. GET was calculated using the V-slope method [2] with MAP and VO_{peak} calculated as the highest mean power output and oxygen consumption, respectively, over a 30-s period [18].

**Original critical power test**

On separate days, each participant completed 3 tests to exhaustion at 80, 100 and 110% MAP following a standardized 10-min warmup at 100 W [18]. During each test, participants were instructed to cycle at their preferred cadence for as long as possible. Tests were terminated once cadence dropped by more than 10 rev·min⁻¹ below the pre-determined preferred cadence for more than 5 s. Consistent with Vanhatalo et al. [28] and Karsten et al. [14], CP and W′ were calculated using linear regression from the power-time, \( P = W′ (1/t) + CP \), mathematical model [32].

**3-min all-out cycling tests**

On different days, 4 tests were carried out to calculate EP and WEP from 2 separate 3-min all-out protocols. 2 tests were carried out against a fixed resistance (i.e. linear mode) and 2 using a fixed cadence (i.e. isokinetic mode). The fixed resistance was setting the ergometer’s linear mode and in line with the protocol described by Vanhatalo et al. [28]. During the isokinetic tests participants cycled at their preferred cadence for the duration of each trial [18]. In this mode, the participants were unable to cycle faster than the selected cadence and an increase in torque resulted in an increase in resistance. Following a 10-min warmup at 100 W, all 3-min tests started with a 30-s period of unloaded cycling at the participant’s preferred cadence. During the final 15 s of this period, the participants were instructed to increase their cadence by 10 rev·min⁻¹ and, after a countdown, were encouraged to attain peak power in the first 5 s of the 3-min tests. During the linear tests, this was achieved by encouraging the participants to cycle at the highest possible cadence throughout the test and it was clearly explained that the test should not be paced. During the isokinetic tests, the participants...
were encouraged to cycle at maximal effort throughout each test. Breath-by-breath analysis and heart rate were measured for all tests to ensure that the participants attained the testing criteria set by Jones et al. [22], i.e., that 1) participants need to be motivated and familiarized with the testing protocol, 3) time-based feedback should not be provided to avoid pacing, 3) participants should be encouraged to maximize cadence throughout the test and 4) attainment of > 95% V\textsubscript{O}\textsubscript{peak} with no decremental trend in V\textsubscript{O}2 observed during the test. A warm-down at 50 W was carried out for 3 min following each trial with additional time provided, if required. All participants were monitored for at least 15 min to ensure their safety before leaving the laboratory. For each of the 3-min tests, EP was calculated as the mean power output over the final 30 s and WEP was calculated as the power-time integral above EP.

Statistical analyses

Shapiro–Wilk tests of normality were carried out on all data prior to analysis. The Greenhouse–Geisser approach was used as a result of the data violating the assumptions of sphericity (Mauchly’s Test of Sphericity, P < 0.001). Consistent with Karsten et al. [18] and Vanhatalo et al. [22], agreement between CP and EP and between W and WEP for both the linear and isokinetic test was measured using a one-way repeated measures ANOVA and limits of agreement (LOA) [4]. To adjust for multiple comparisons during the one-way repeated measures ANOVA, the Bonferroni procedure was used. The reliability between testing sessions was measured using coefficient of variation (COV), intraclass correlation coefficients (ICC) and standard error of measurement (SEM). Consistent with Karsten et al. [18], the error associated with predicting EP and WEP from linear regression methods was measured using standard error of estimates (SEE). In addition, Pearson’s product moment correlation coefficients were carried out to measure relationships. Statistical significance was accepted at P < 0.05 with all data reported as means ± SD.

Results

The mean V\textsubscript{O}2\textsubscript{peak} and peak blood lactate for each testing protocol can be found in Table 1. Critical power and W were calculated from the power-time mathematical model resulted in an r^2 value of 0.97 ± 0.02. A one-way repeated measures ANOVA showed no significant differences between EP and isokinetic and CP (2.7 ± 0.5 W vs. 27.4 ± 2.6 W, P = 0.377, 95% CI of 0.03 to 29.8 W). There were significant differences between EP-linear and CP (2.7 ± 0.5 W vs. 24.9 ± 2.6 W, P = 0.004, 95% CI of 30.22 to 46.75 W). The limits of agreement between CP and the EP estimates from the isokinetic and linear tests are shown in Fig. 1.

Significant differences were identified between isokinetic and CP (15.8 ± 5.0 kJ vs. 22.7 ± 5.0 kJ, P < 0.001, 95% LOA of −7.12 ± 4.7 kJ) and between WEP-linear and W (11.5 ± 4.7 kJ vs. 22.7 ± 5.0 kJ, P < 0.001, 95% LOA of −9.27 ± 8.9 kJ). The limits of agreement between WEP-isokinetic and W and between WEP-isokinetic and W are illustrated in Fig. 2. The standard error of estimates and Pearson’s product moment correlation coefficients between CP-isokinetic and EP, CP-linear and CP, WEP-isokinetic and W and WEP-linear and W are shown in Table 2.

The coefficient of variation in EP-isokinetic. EP-linear, WEP-isokinetic and WEP-linear was 1.93, 1.17, 8.44 and 5.39%, respectively, between tests 1 and 2. The intraclass correlation coefficient for CP-isokinetic was 0.97 (95% CI = 0.91 to 0.99, P < 0.001, CP-linear was 0.99 (95% CI = 0.98 to 0.99), P < 0.001, WEP-isokinetic was 0.94 (95% CI = 0.90 to 0.98), P < 0.001 and WEP-linear was r = 0.98 (95% CI = 0.93 to 0.99), P < 0.001 (Table 3).

Discussion

The results of the present study suggest that the 3-min all-out cycling test is an isokinetic mode provides a reliable measure of CP and a valid estimate of CP. Although the 3-min all-out cycling test in an isokinetic mode provides a reliable measure of EP, the results suggest that the linear mode does not provide a valid estimate of CP. Results also suggest that neither 3-min test mode provides a reliable measure of WEP or a valid estimate of W, with both the isokinetic and linear mode significantly underestimating W [Fig. 3].

Karsten et al. [18] found while providing a reliable measure of EP, the 3-min all-out test carried out in the isokinetic mode overestimated CP by approximately 37 W when using the power-time mathematical model. However, Dekerle et al. [16] found that there was no significant difference between CP and W when the 3-min all-out test was carried out at 60 and 100 rev min\(^{-1}\). In contrast, Talalay et al. [27] found that CP underestimated W by approximately 11 W when carried out in isokinetic mode. The results from the present study also contrast with the research carried out in the linear mode by Vanhatalo et al. [20, 21, 22]. Where Vanhatalo et al. reported near identical CP and EP, the present study observed significant differences between CP-linear and CP (27.5 ± 1.4 W vs. 24.9 ± 2.6 W, P = 0.004). It would appear that the 3-min all-out cycling test is isokinetic mode provides a valid estimate of CP; however, the results of this study raise questions regarding the reliability of this approach.

![Image](image1.png)

Table 1 Mean values (± SD) for VO2peak, peak blood lactate, CP and W observed during each testing session.

<table>
<thead>
<tr>
<th>Condition</th>
<th>VO2peak (L min(^{-1}))</th>
<th>Peak blood lactate (mmol L(^{-1}))</th>
<th>CP (kJ)</th>
<th>W (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rang protocol</td>
<td>4.4 ± 0.6</td>
<td>11.3 ± 0.6</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Original CP protocol</td>
<td>4.3 ± 0.3</td>
<td>11.3 ± 2.1</td>
<td>244.9 ± 38.2</td>
<td>22.7 ± 2.6</td>
</tr>
<tr>
<td>3-min all-out test (isokinetic)</td>
<td>4.5 ± 0.2</td>
<td>12.5 ± 4.2</td>
<td>240.9 ± 23.3</td>
<td>15.6 ± 3.6*</td>
</tr>
<tr>
<td>3-min all-out test (linear)</td>
<td>4.4 ± 0.4</td>
<td>12.8 ± 2.1</td>
<td>275.1 ± 41.2*</td>
<td>13.5 ± 4.7*</td>
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</table>

* Significantly different from the original CP protocol (P < 0.05)

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regarding the validity of the 3-min all-out test when carried out against a fixed resistance following the protocol set by Vaahakalo et al. [28]. For both testing modes, it would appear that the reliability of the 3-min all-out cycling test is good. In line with previous research [18, 21], reliability of EP-isokinetic and EP-linear between testing sessions was seen to have a coefficient of variation of less than 5% (1.93% and 1.17% respectively) [Hopkins WC. A new view on statistics. Internet Society for Sport Science (2006). In internet: http://www.sportsci.org/resource/stats/ (Accessed 29 November 2016)].

Data collection during the present study differed from Karston et al. [18] only with the additional measurement of pulmonary
gases during all tests. During all testing sessions of the present study, participants met the criteria of a successful test required by Jones et al. [22]. On only one occasion was a participant required to repeat one of the testing sessions, this the result of a decremental trend in \( V_{O_2} \) during the final 5 s of one of the 3-min all-out tests. Without the measurement of pulmonary gases, Karsten et al. [18] were unable to state with certainty whether all of the above criteria were met during all of their tests, and it could be suggested that the participants in their study may not have exercised at a high enough intensity throughout each test. The physical demands of participating in this study were high, with 8 exhaustive testing sessions carried out by each participant. A randomized trial order was carried out to reduce the likelihood of any changes in fitness affecting the results; however, it should be acknowledged as a potential limitation that a few participants have affected the calculation of both CP and \( W' \). Another limitation of this study was the lack of a verification procedure following the calculation of CP [8].

A key result of this study was the significant overestimation of \( W' \) when the 3-min all-out cycling test was carried out in the linear mode, especially when compared to the original research by Vanhatalo et al. who found CP and CP to be almost identical [28]. These differences could be explained by the cadence selected in order to calculate the linear factor for each participant with previous research suggesting that CP is sensitive to small changes in cadence [18]. In order to calculate the linear factor, each participant was asked for their preferred cadence, and it was noted that a number of participants stated a range between 50–100 rev-min\(^{-1}\). This cadence selection could help explain why differences are noted within the literature in both isokinetic and linear modes and it is probable that the cadences selected for some participants were too low. Typically, a trained cyclist will state that their preferred cadence is between 90–100 rev-min\(^{-1}\) but this would depend on the demands of the ride, for example, during a time-trial or mountain stage [1]. A study by Vanhatalo et al. [30] found that CP can be reduced by approximately 10 W when using a cadence of 10 rev-min\(^{-1}\) above the participant’s preferred cadence. Similarly, Dekker et al. [10] evaluated the 3-min all-out test in isokinetic mode at both 100 and 100 rev-min\(^{-1}\) and reported a 14% lower EP upon the adoption of the higher cadence. These reductions in CP were attributed to the fact that fast twitch muscle fibres are more susceptible to fatigue when pedaling at higher cadences [10]. This results in a fast decline in power output over the duration of the test, which in turn produces a lower EP during the final 5 s. In order to overcome the potential limitation of the 3-min all-out cycling test when carried out against fixed resistance, alternative procedures have been suggested [8, 11]. These include the use of a percentage of body mass value being used to determine the testing resistance with positive results seen. Although the results from the present study conclude that the 3-min all-out test against fixed resistance does not provide a valid estimation of CP, it is possible that this is due to the methods used to calculate this resistance. It is suggested that the original method for calculating this resistance (e.g., preferred cadence) is susceptible to error, which may lead to inaccurate testing results. A more recent study by Karsten et al. [19] concluded that CP can be determined during a single session of 90 min. However, results also found that this testing protocol does not provide valid estimates of \( W' \) and more research is required to determine whether a single session test protocol can be used as a valid method to identify both CP and \( W' \).

The estimates of \( W' \) were significantly lower for both isokinetic (7.1 kJ) and linear modes (9.2 kJ). These results suggest that neither testing mode provides a reliable measure of CP or a valid estimate of \( W' \). Although these differences were larger than shown in previous studies, several authors have reported that the 3-min all-out test carried out in both linear isotonic modes underestimates \( W' \) [18,28]. Previous studies have also suggested that with significant variations in WEP observed between testing sessions, this parameter lacks sensitivity and is, in effect, meaningless [10, 21]. Vanhatalo et al. [28] suggested that these results may be due to the differences in power measurement between the 3-min all-out cycling test and the constant-power tests when using the Lode Excalibur Sport. They explain that during the first 10 s of the 3-min all-out cycling test there is an acceleration of the Lode’s flywheel when performed in the linear mode. However, this acceleration is absent during the constant-power trials used to calculate W using the original protocol. Vanhatalo et al. [28] suggest the use of the isokinetic mode or SLM cranks to overcome this problem as they are unaffected by flywheel inertia. However, the present study found that WEP was significantly lower than \( W' \) when tested in isokinetic mode, supporting the findings of Karsten et al. [18] It might be suggested that a 3-min all-out cycling test is not long enough to fully deplete \( W' \) in all individuals. Therefore, more research focusing on the finite work capacity during exhaustive exercise is recommended using trained cyclists. It should be noted that the research by Vanhatalo et al. [28–30] was carried out using participants from a mixture of athletic backgrounds and that they may not have all been fully accustomed to all-out cycling. Before the 3-min all-out cycling test can be used with confidence to estimate CP, additional research is required into the effect cadence has on setting the test resistance.

Conclusion

The main finding of this study suggests that the 3-min all-out cycling test performed in isokinetic mode is reliable and can also be used to estimate critical power. It would appear that although reliable, the 3-min all-out cycling test performed in linear mode does not provide a valid estimate of CP when following the methods used by Vanhatalo et al. [28]. It is suggested that care should be taken when selecting a testing mode to complete the 3-min all-out cycling test. Furthermore, although the 3-min all-out cycling test is successfully used within applied research, the results of the present study highlight that there are potential causes for concern with the protocol used. It is suggested that future research focuses on the methods used to set the fixed resistance and to follow on from the work of Dirks et al. [11]. Results also suggest that neither testing mode provides a reliable or valid estimate of \( W' \); which would appear to be more comparable to previous studies. Cadence selection, the duration of the test and also the testing ergometer and mode may all affect the estimates of CP and \( W' \).
Acknowledgements

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Conflict of interest

The authors have no conflict of interest to declare.

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A.2 Journal of Sports Sciences

The 3-minute all-out cycling test is sensitive to changes in cadence using the Lode Excalibur Sport ergometer

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ABSTRACT

This study investigated the effect cadence has on the estimation of critical power (CP) and the finite work capacity (W) during the 3-minute all-out cycling test. Ten participants completed 8 tests: 1) an incremental test to calculate gas exchange threshold (GET), maximal aerobic power (MAP) and peak oxygen uptake (VO2peak); 2–4) three time-to-exhaustion tests at 80, 100 and 105% MAP to calculate CP and W; 5–7) four 3-minute all-out tests to calculate end power (EP) and work done above EP (WEP) using cadences ranging from preferred +10 rev-min⁻¹ to set the fixed resistance. Significant differences were seen between CP and EP at 260.5 ± 22.6 W vs. 299.6 ± 26.1 W, P < 0.001, CP and EP at 260.5 ± 22.6 W vs. 303.6 ± 24.0 W, P < 0.001; and between CP and EP at 260.5 ± 22.6 W vs. 290.0 ± 28.0 W, P = 0.002. No significant differences were seen between CP and EP at 10 (267.5 ± 22.6 W vs. 278.1 ± 30.9 W, P = 0.331). Significant differences were seen between W and WEP at all tested fixed resistances. EP is reduced when cycling at higher than preferred cadences, providing better estimates of CP.

KEYWORDS

Exercise testing; training zones; fatigue

INTRODUCTION

Critical power (CP) was originally described as the highest rate of aerobic metabolism that can be sustained without fatigue (Monod & Scherrer, 1965). However, more recently, Burnley, Vanhatalo, and Jones (2013), have demonstrated that peripheral fatigue does develop below critical power. This concept has been investigated in cycling for over 30 years and it is suggested that CP defines the boundary between the heavy and severe exercise intensity domains within an error of approximately 5% (Poole, Burnley, Vanhatalo, Rossiter, & Jones, 2016). The CP test allows the determination of two parameters: an aerobic component, which is rate- but not capacity-limited (CP), and an anaerobic component, which is capacity- but not rate-limited (W) (Jones, Vanhatalo, Burnley, Morton, & Poole, 2016). Although CP and W can provide coaches with information to inform athlete training, a typical testing session requires 3-4 time-to-exhaustion (TTE) cycling tests, which is often overly onerous on the athlete (Abillo, Peiffer, & Laursen, 2009; Gaesser & Wilson, 1968; Jenkins & Quigley, 1996; Smith & Hill, 1993).

The impractical nature of the original CP test protocol has led to the development of the 3-minute all-out cycling test which aims to provide estimates of CP and W (Vanhatalo, Dout, & Burnley, 2007). Cycling against a fixed resistance, the 3-minute all-out test aims to fully deplete W within the first 150 seconds, resulting in a plateau of power output in the final 30 seconds of the test. The final power observed from this test, end power (EP), and the work above EP (WEP), should in theory be the same as CP and W calculated from the original testing protocol. Vanhatalo et al. (2007) found that the 3-minute all-out cycling test provided near identical estimations of CP and similar, albeit slightly lower, estimations of W. However, more recent studies have found that EP overestimates CP by approximately 5–12%, with WEP significantly underestimating W (Dekerle, Barstow, Reegan, & Carter, 2014; Karsten, Jobson, Hopker, Passfield, & Beedle, 2014; Wright, Bruce-Low, & Jobson, 2017). During the studies by Dekerle et al. (2014) and Karsten et al. (2014), the 3-minute all-out cycling test was carried out using a fixed cadence of between 60-100 rev-min⁻¹ (isokinetic mode) rather than against a fixed resistance (linear mode) as used by Vanhatalo et al. (2007). This difference in testing mode may help to explain why both Dekerle et al. (2014) and Karsten et al. (2014) found that the 3-minute all-out test overestimates CP. However, a more recent study by Wright et al. (2017) evaluated CP using both isokinetic and linear modes, with results suggesting that EP determined from the linear mode significantly overestimated CP. Results also suggested that EP determined from the isokinetic mode provided a closer estimation of CP. The results from the studies above would suggest that the differences observed between CP and EP are not necessarily attributable to the testing mode used during the 3-minute all-out cycling test.

Previous research has demonstrated that critical power is sensitive to changes in cadence when calculated from multiple TTE tests. Barker, Poole, Noble and Barstow (2006) found that critical power is reduced by approximately 18 W when the TTE tests were performed at 100 rev-min⁻¹ compared to 60 rev-min⁻¹. It has also been demonstrated that the 3-minute all-out cycling test is sensitive to small changes in the cadence used to set the ergometer’s fixed resistance (Vanhatalo, Doutt,
When the test protocol is carried out against a fixed resistance, it is important to ensure that this resistance is individualised for each athlete. The Lode Excalibur Sport ergometer, as used by Vanhatalo et al. (2007), uses the following equation to set the pedalling resistance: linear factor = power/preferred cadence\(^2\), Rumley, Deutel, and Vanhatalo (2006) suggested that power should correspond to the power output midway between gas exchange threshold (GET) and \(V_O_{2\text{peak}}\) (50%). The linear factor is very sensitive to changes in cadence due to the squared function within the equation. It is therefore important to ensure that a correct cadence is selected for each participant, especially when the term “preferred cadence” is ambiguous. Vanhatalo et al. (2008) demonstrated that EP is sensitive to changes in the cadence used to set the linear factor. Their findings suggested that, although unaffected by selecting a lower cadence, EP was reduced by approximately 10 W when using a cadence of 60 rev min\(^{-1}\) compared to 70 rev min\(^{-1}\). In contrast to Vanhatalo et al. (2008), Delisle et al. (2014) found that WP was significantly increased when tested at a higher cadence. In a similar study, de Lucas et al. (2014) found a significant reduction in EP on the adoption of a higher cadence (100 vs. 60 rev min\(^{-1}\)) but no differences in WP were observed between cadences. The results from these studies highlight the importance of selecting the correct cadence before carrying out the 3-minute all-out cycling test.

The aim of the present study was to investigate the effect of cadence on the determinations of EP and WP from a 3-minute all-out cycling test. It was hypothesised that higher cadences would result in a reduction in both EP and WP.

**Methods**

**Participants**

Ten trained (De Pauw et al., 2013) male cyclists (mean ± SD: age 36 ± 5 years, body mass 78.6 ± 6.6 kg, maximum aerobic power (MAP) 368 ± 29 W, \(V_O_{2\text{peak}}\) 4.7 ± 0.4 L min\(^{-1}\)) volunteered to take part in this study. All participants provided written informed consent and a health screening (PARQ, resting blood pressure, 12-lead ECG) was carried out prior to testing. The study was conducted in accordance with the Declaration of Helsinki and was approved by the host university’s ethics committee.

Participants took part in 8 tests to calculate GET, MAP, \(V_O_{2\text{peak}}\), CP, W and the estimates EP and WP, with each testing session separated by a minimum of 48 hours. Other than rest, one for determination of GET, \(V_O_{2\text{peak}}\) and MAP, all tests were carried out in a randomized order. All tests were carried out using an electronically braked cycle ergometer (Excalibur Sport, Lode, The Netherlands), with the participant’s own shoes and pedals used. The bike settings for each participant (e.g., seat and bar height) were noted on the first visit to ensure that they could be replicated during subsequent testing sessions. Prior to each testing session, participants were instructed to avoid heavy exercise for 24 hours and fast intake for 2 hours. Participants were also instructed to drink 350 ml of water 2 hours prior to testing. Strong verbal encouragement was provided during each test but no feedback regarding heart rate, power output or time was provided.

**GET, MAP and \(V_O_{2\text{peak}}\) protocol**

Starting at 150 W, each participant completed a maximal incremental ramp test (20 W min\(^{-1}\)) to calculate GET, MAP and \(V_O_{2\text{peak}}\) (Davis et al., 1982). Throughout the test, breath-by-breath expired air (Metamax CPX, Jaeger, Germany) and heart rate (RCX5, Polar, Finland) were recorded at 5-second intervals. On completion of the test, a capillary blood lactate sample (Biosen C-Line, EKF Diagnostics, Germany) was taken from the fingertip. GET was calculated using the V-slope method outlined by Beaver, Wasserman, and Whipp (1980). MAP was calculated as the highest 30-second mean power output and \(V_O_{2\text{peak}}\) as the highest 30-second average in \(V_O_2\) (Kasten et al., 2014; Robergs, Dwyer, & Astorino, 2010).

**Original critical power test**

In order to calculate CP and W, each participant completed three separate TTE tests at 80, 100 and 105% MAP (Kasten et al., 2014; Monod & Schnurr, 1995). Following a 10-minute warm-up at 100 W, each participant was instructed to cycle at their preferred cadence until volitional exhaustion with heart rate and \(V_O_2\) measured throughout. Each test was terminated when the cadence dropped by more than 10 rev min\(^{-1}\) below the participant's preferred cadence. Consistent with Vanhatalo et al. (2007) and Kasten et al. (2014), CP and W were calculated using linear regression from the power-time, \(P = W/T + CP\) mathematical model.

**3-minute all-out cycling tests**

On separate days, EP and WP were also calculated from four 3-minute all-out cycling tests. All participants had experience of the 3-minute all-out cycling test from a separate study and had completed a minimum of 4 tests in the previous 12 months. For each test, a fixed resistance was used in line with the protocol described by Vanhatalo et al. (2007) and using the following equation: resistance = 50% preferred cadence\(^2\). Prior to testing, each participant was asked to self-select their preferred cadence, and this was used to set the resistance for each test. 1) participant’s preferred cadence (EP-preferred, and WP-preferred), 2) preferred cadence - 5 rev min\(^{-1}\) (EP-S and WP-S), 3) preferred cadence + 5 rev min\(^{-1}\) (EP+5 and WP+5) and 4) preferred cadence + 10 rev min\(^{-1}\) (EP+10 and WP+10). Prior to each test, participants were required to complete a standardized 10-minute warm-up at 100 W. Each 3-minute all-out test started with an unloaded period of cycling for 30 seconds with participants instructed to increase their cadence to approximately 110 rev min\(^{-1}\) in the final 10 seconds. Following a countdown, participants were instructed to cycle maximally from a seated position and were encouraged to reach peak power output within the first 5 seconds of the 3-minute tests. It was clearly
explained that maximal exertion should be given throughout the test. Heart rate and VO\(_2\) were measured throughout each test with a post-test capillary blood lactate sample taken immediately upon completion. Participants were required to carry out a 5-minute warm down at 50 W to reduce the chances of syncopy or nausea with all participants closely monitored for at least 15 minutes after each test.

**Statistical analyses**

Shapiro-Wilk tests of normality were carried out on all data prior to analysis. A one-way repeated-measures ANOVA, limits of agreement (LoA) and correlation coefficients were used to compare the agreement between CP with EP and W with WEP at each cadence. During the one-way repeated-measures ANOVA, the Bonferroni correction was used to adjust for multiple comparisons. A one-way repeated measures ANOVA was also used to compare EP and WEP between testing sessions. Effect sizes (ES) were also calculated using Cohen's d, trivial (<0.19), small (0.20–0.69), medium (0.50–0.79) and large (>0.80) (Cumming, 2014). The error associated with predicting EP and WEP from linear regression methods was measured using standard error of estimates (SEE). All data are reported as mean ± SD with statistical significance accepted at \(P < 0.05\).

**Results**

Comparisons between \(V\text{O}_{2\text{peak}}\), peak power, EP, peak cadence, and end cadence and WEP during each 3-minute all-out test are displayed in Table 1. The mean cadences observed during the incremental ramp test and the three TTE tests can be found in Table 2. A one-way repeated measures ANOVA showed significant differences between CP and EP-preferred (268 ± 23 W vs. 297 ± 26 W, \(P = 0.001\), 95% LoA of 36 ± 23 W, ES = 1.53) and between CP and EP-preferred-WEP (268 ± 23 W vs. 290 ± 28 W, \(P = 0.002\), 95% LoA of 23 ± 23 W, ES = 0.86). At the highest cadence, results showed no significant difference between CP and EP-preferred-WEP (268 ± 23 W vs. 275 ± 31 W, \(P = 0.331\), 95% LoA of 11 ± 26 W, ES = 0.37) (Figure 1).

Significant differences were seen between W and EP-preferred (20.5 ± 5.1 kJ vs. 11.2 ± 4.5 kJ, \(P < 0.001\), 95% LoA of -6.6 to 10.1 kJ, ES = 1.93), W and EP-preferred-WEP (20.5 ± 5.1 kJ vs. 12.6 ± 4.0 kJ, \(P = 0.017\), 95% LoA of -5.0 to 11.8 kJ, ES = 0.4), W and EP-preferred-WEP (20.5 ± 5.1 kJ vs. 11.0 ± 4.4 kJ, \(P = 0.003\), 95% LoA of -6.4 to 10.4 kJ, ES = 1.90) and WEP and EP-preferred-WEP (20.5 ± 5.1 kJ vs. 10.5 ± 4.8 kJ, \(P = 0.012\), 95% LoA of -8.9 to 11.8 kJ, ES = 1.94) (Figure 2).

The SEE and correlation coefficients between CP with EP and between W with WEP at each cadence are shown in Table 2.

Results from a one-way repeated measures ANOVA showed no significant differences between EP-preferred and EP-preferred-WEP (297 ± 26 vs. 290 ± 28 W, \(P = 0.073\)) or between EP-preferred-WEP and EP-preferred-WEP (297 ± 26 vs. 290 ± 28 W, \(P = 0.073\)). However, significant differences were seen between EP-preferred-WEP and EP-preferred-WEP (297 ± 26 vs. 290 ± 28 W, \(P = 0.001\)). It should also be noted that significant differences were seen between EP-preferred-WEP and all other cadences (\(P < 0.05\)). No significant differences were found between WEP-preferred and WEP-preferred-WEP (112 ± 4.5 vs. 12.6 ± 4.6 kJ, \(P = 0.094\)), WEP-preferred-WEP (112 ± 4.5 vs. 11.0 ± 4.4 kJ, \(P = 1.00\)) or with WEP-preferred-WEP (112 ± 4.5 vs. 10.9 ± 4.3 kJ, \(P = 1.00\)). Furthermore, no significant differences were seen between any of the cadences (\(P > 0.05\)). Oxygen uptake during the 3-minute all-out cycling test is highlighted in Figure 3 and demonstrates how 95% ramp test \(V\text{O}_{2\text{peak}}\) was attained within the first 90 seconds and then maintained for the duration of the test in line with the recommendations set by Jones et al. (2010).

Table 3 highlights the mean cadence, \(V\text{O}_{2\text{peak}}\) and time to exhaustion during each testing session. No significant differences were seen between the peak oxygen uptake observed during the ramp test and the 80% MAP TTE (4.8 ± 0.4 vs. 4.6 ± 0.4 L·min\(^{-1}\), \(P = 0.820\)), 100% MAP TTE (4.8 ± 0.4 vs. 4.5 ± 0.6 L·min\(^{-1}\), \(P = 1.000\)) or 105% MAP TTE (4.8 ± 0.4 vs. 4.6 ± 0.5 L·min\(^{-1}\), \(P = 1.000\)) with 95% ramp test \(V\text{O}_{2\text{peak}}\) observed for all TTE conditions. The \(F\)-squared value for the 1/time mathematical model ranged from 0.001-0.000 for all participants with standard error values of 0.3-15.8 W for CP and 0.6-4.5 W for WEP.

**Discussion**

The results of this study suggest that CP calculated from the 3-minute all-out cycling test is affected by the cadence used to set the fixed resistance, with a reduction in EP observed at higher cadences. Results also suggest that selecting cadence 10 min·\(^{-1}\) above preferred cadence provides the closest estimation of CP, with EP-preferred-WEP and EP-preferred-WEP significantly overestimating CP. Additionally, the results suggest that WEP is unaffected by cadence and that W is significantly underestimated at all cadences tested. These results highlight the importance of selecting the correct cadence when setting the fixed resistance prior to undertaking the 3-minute all-out cycling test.

The 3-minute all-out cycling test has been extensively investigated (Dechleer et al., 2014; de Lucas et al., 2014; Dicks, Jamnick, Murray, & Pettitt, 2016; Francis, Quinn, Arman, &
Table 2. Standard error of estimates and Pearson's product-moment correlation coefficients between CP with EP and between W with WEP calculated at each

cadence.

<table>
<thead>
<tr>
<th>Pair</th>
<th>r</th>
<th>SEE</th>
</tr>
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<tbody>
<tr>
<td>CP vs. EP-preferred</td>
<td>0.91</td>
<td>0.01</td>
</tr>
<tr>
<td>CP vs. EP-S</td>
<td>0.97</td>
<td>0.00</td>
</tr>
<tr>
<td>CP vs. EP-S</td>
<td>0.91</td>
<td>0.01</td>
</tr>
<tr>
<td>CP vs. EP-S</td>
<td>0.92</td>
<td>0.00</td>
</tr>
<tr>
<td>W vs. EP-preferred</td>
<td>0.68</td>
<td>0.03</td>
</tr>
<tr>
<td>W vs. EP-S</td>
<td>0.50</td>
<td>0.46</td>
</tr>
<tr>
<td>W vs. EP-S</td>
<td>0.67</td>
<td>0.47</td>
</tr>
<tr>
<td>W vs. EP+10</td>
<td>0.52</td>
<td>0.22</td>
</tr>
</tbody>
</table>

LaRoche, 2010; Johnson, Sexton, Placek, Murray, & Pettitt, 2011; Waldron, Gray, Furlan, & Murphy, 2016; however, some recent studies have found that EP overestimates CP (Bergstrom et al., 2014; Karsten et al., 2014; Wright et al., 2017). These studies raise questions about the protocols used when performing the 3-minute all-out cycling test. Concerns about the 3-minute all-out test were also raised by Mattioni Matutana, Feir, McLay, & Munas (2016). Although the mean difference between CP and EP were not significantly different (253 ± 44 W vs. 250 ± 51 W), the authors concluded that care should be taken due to the wide limits of agreement observed from the Bland-Altman plots. The original research by Vanhatalo et al. (2007) concluded that the 3-minute all-out test provided a reliable measure of CP and WEP, and an almost identical estimation of CP. However, further research found that EP is reduced by approximately 10 W upon the selection of a higher cadence (preferred =10 rev·min⁻¹) but that it is unaffected when tested at a slightly lower cadence (preferred =5 rev·min⁻¹) (Vanhatalo et al., 2008). The results of the present study support these findings, although slightly larger reductions in EP of approximately 20 W were observed at the highest cadence (10 rev·min⁻¹). Results also suggest that WEP is less sensitive and remains consistent across cadences. These results are supported by those found by Vanhatalo et al. (2008) and Chidnok et al. (2013) who reported that WEP was unaffected by pacing during a 3-minute all-out cycling test. The effect of cadence on EP and WEP has also been investigated when using the isokinetic ergometer mode, with results showing that EP is reduced upon the adoption of a higher cadence (Dekker et al., 2014; de Lucas et al., 2014). Although slightly larger differences of approximately 30–50 W were seen between conditions when tested in isokinetic mode, it should be noted that a greater range in cadences were used (60–100 rev·min⁻¹) in the studies by Dekker et al. (2014) and de Lucas et al. (2014).

With results from the present study demonstrating that EP is reduced at higher cadences, the importance of selecting the correct cadence when performing the 3-minute all-out cycling test is highlighted. It could be assumed that the preferred cadences provided by each participant in the present study were not high enough to elicit similar results to those reported previously (Vanhatalo et al., 2007, 2008). It can be seen from Table 2 that the participants naturally chose a higher cadence for the shorter, and higher power output TTF tests (89.5 ± 46 rev·min⁻¹ at 80% MAP compared to 96.2 ± 34 rev·min⁻¹ at 15% MAP) differing from their self-selected preferred cadence of 91.0 ± 1.6 rev·min⁻¹. Abbiss et al. (2009) suggested that, for ultra-endurance events, a cadence of between 70–90 rev·min⁻¹ may be optimal due to the reduced energy cost and increased cycling economy observed at lower cadences. However, for endurance events and short duration sprint events, cadences of between 90–100 and 110 rev·min⁻¹, respectively, may be advised to increase power output (Abbiss et al., 2009; Sargeant, Holmville, & Young, 1981).

Figure 1. Bland-Altman plots showing the limits of agreement between CP and EP-preferred (a), CP and EP-S (b), CP and EP+5 (c) and CP and EP+10 (d). The solid line represents the mean difference in power output and the dashed line represents the 95% limits of agreement.
The effect of cadence on muscular fatigue has been extensively investigated with higher cadences leading to a faster decline in muscular fatigue (Beden & Sargeant, 1991; Hill, Smith, Leuschel, Charte, & Miller, 1995; Vansballe et al., 2008). Due to the physiological basis of the 3-minute all-out cycling test, it is imperative that the finite work capacity is exhausted within the first 150 seconds of the test. A faster decline in fatigue is therefore likely to result in a lower EP, which, in turn, may provide a more accurate estimate of CP. McCartney, Obminkski, and Heinecker (1985) found that the decline in average power observed during a 30-second maximal effort was less at 60 rev-min⁻¹ compared to 140 rev-min⁻¹. Vanhatalo et al. (2008) have suggested that an increase in fatigue at higher cadences could be due to the fatiguing qualities of type I and II muscle fibres. It was suggested that the high cadences observed during the initial stages of the 3-minute all-out test, especially during the high cadence condition, results in sub-optimal cadences for peak power production. Delfos et al. (2014) also observed reductions in EP when using a higher cadence during the 3-minute all-out test, suggesting that fast twitch muscle fibres are less fatigue resistant. These results...
highlight the challenges faced when using the participant’s preferred cadence to set the fixed resistance during the 3-minute all-out cycling test. The effect of cadence on muscular fatigue may also influence the original CP protocol. Green, Bishop, and Jenkins (1995) found that W’ is significantly increased if the end-test cadence is reduced from 70 to 60 rpm min⁻¹. To standardise testing sessions, the TTE tests were terminated when the participants’ cadence dropped by more than 10 rpm min⁻¹ below their preferred cadence. However, they were not instructed to maintain a set cadence throughout each test. Table 2 highlights the differences in mean cadence during each test and, with a difference of −7 rpm min⁻¹ between the 80, 100 and 105% TTE tests, it is reasonable to assume that this could affect the calculations of both CP and W’. It is also possible that the accuracy of the original CP protocol may have been affected by the selection of only three TTE tests. Although these TTE tests have successfully been used to calculate CP and W’ (de Lucas et al., 2014), some authors have used five or more TTE tests (Poole, Ward, Gardner, & Whipp, 1998). In a recent study by Mattoni Maturana, Fontana, Pogliaghi, Passfield, and Murias (2017), the authors concluded that the mathematical model 1, number and duration of TTE tests used can affect the calculation of CP and W’. Although their findings support the use of the linear 1/time mathematical model from three TTE tests, CP may vary by approximately 12 W depending on the duration of each test. All participants in the present study reached exhaustion within 2-15 minutes for each TTE test, as stipulated by Jones et al. (2010). However, the results from the Mattoni Maturana et al. (2017) study may suggest that slightly longer TTE tests should be included (e.g., 320 minutes) to ensure accurate estimations of CP. Participants also reached a post-test blood lactate above 8 mmol L⁻¹ and an end-test RER of >1.15 during all TTE tests suggesting that a maximal effort was given during each TTE test.

A limitation of the present study is that a CP validation test was not included to ensure that a physiological steady state had been established (Mattoni Maturana et al., 2016). However, this is a common limitation within the literature and it should also be noted that the original research by Vaydaio et al. (2007) on the 3-minute all-out cycling test did not include a CP validation test. Based on the concerns above it is reasonable to suggest that the linear 1/time model may not have provided the most accurate method for calculating CP. Without completing a CP validation test, it is not possible to say with certainty that the original or 3-minute all-out cycling test provided a true estimation of CP, and therefore, the demarcation between the heavy and severe exercise intensity domains.

It has been demonstrated how cadence selection can affect the accuracy of CP testing protocols. These results have led some authors to investigate alternative testing protocols (Clark, Murray, & Pettitt, 2013; Dicks et al., 2016). Clark et al. (2013) noted that some participants failed to complete the 3-minute all-out cycling test when the resistance was set according to the protocol described by Vaydaio et al. (2007). Clark et al. (2013) investigated the possibility of setting the fixed resistance using a percentage of body mass (%BM) and took into consideration the fitness levels of each participant. 3% BM for recreationally active, 4% BM for anaerobic and aerobic athletes, and 5% BM for endurance athletes. Dicks et al. (2016) have also investigated an alternative testing protocol by estimating 50% from a self-reporting of physical activity rating. These authors concluded that alternative testing protocols can be used for the determination of CP and W’ from a single testing session. These protocols remove the need to carry out a ramp test to calculate GET and VO2peak, both prerequisites for setting the resistance using the original linear factor equation. However, although they have been found to provide a similar estimation of CP and W’, both rely on making calculations based on estimates and for the participants to self-select their current fitness level.

Although the 3-minute all-out cycling test has been demonstrated to provide similar estimations of CP, there remains a concern about its sensitivity to the fixed resistance used as a result of cadence selection. It is recommended that future research investigates the differences in cadences on a wider range of cyclists, from novice to elite, with the aim of providing a more definitive method for identifying the participant’s preferred cadence. Alternatively, a field-based all-out cycling test should be investigated to focus on the physiological underpinning of the 3-minute all-out cycling test rather than the testing protocol and ergometer. Finally, it is essential that future research physiologically validates CP to ensure that the results obtained have a practical application.

Conclusion

The key finding of this study suggests that the 3-minute all-out cycling test is sensitive to changes in cadence. Results show that CP was reduced upon the adoption of higher cadences; an increase of 10 rpm min⁻¹ above preferred cadence resulted in an NP similar to CP calculated from the original CP protocol. Results also supported previous research to suggest that W’ is not affected by changes in cadence, although it remains significantly lower than W’. Future research should investigate how an athlete’s “preferred” cadence is determined prior to using the 3-minute all-out cycling test to inform training and race strategy. Furthermore, a physiological validation of the calculation of CP should be included in all future research.

Disclosure statement

No potential conflict of interest was reported by the authors.
Ethical approval
All procedures in studies involving human participants were in accordance with the ethical standards of the institutional review committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent
Informed consent was obtained from all individual participants included in the study.

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References


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The Reliability and Validity of the PowerTap P1 Power Pedals Before and After 100 Hours of Use

James Wright, Thomas Walker, Scott Bumet, and Simon A. Jobson

Purpose: To (1) evaluate agreement between the PowerTap P1 (P1p) and the Lode Excelsior Sport cycle ergometer, (2) investigate the reliability of the P1 pedals between repeated testing sessions, and (3) compare the reliability and validity of the P1 pedals before (P1b) and after (P1a) ~100 h of use. Methods: Ten participants completed four 5-min submaximal cycling bouts (100, 150, 200, and 250 W), a 2-min time trial, and two 10-s all-out sprints on 2 occasions. This protocol was repeated after 15 mo and ~100 h of use. Results: Significant differences were seen between the P1b pedals and the Lode Excelsior Sport at 100 W (P = 0.04), 150 W (P = 0.06), 200 W (P = 0.02), and 250 W (P = 0.02). After ~100 h of use, the P1a pedals did not significantly differ from the Lode Excelsior Sport at 100 W (P = 0.39), 150 W (P = 0.43), 200 W (P = 0.28), and 250 W (P = 0.18), during the 2-min time trial (P = 5.8), or during the all-out sprints (P = 4.1). The coefficient of variation for the P1b and P1a pedals ranged from 0.6% to 1.3% and 0.5% to 2.0%, respectively, during the submaximal cycling bouts. Conclusion: The P1 pedals provide valid data after ~100 h of laboratory use. Furthermore, the pedals provide reliable data during submaximal cycling, even after prolonged use.

Keywords: power meter, ergometer, laboratory testing, field testing

Physiological testing is frequently performed on a laboratory-based ergometer and is an essential aspect of training for competitive cyclists. The Lode Excelsior Sport is an electronically braked cycle ergometer commonly used in sport-science research and is often regarded as a gold standard in testing ergometers.

The development of the cycle-mounted power meter has provided athletes, coaches, and researchers with the opportunity to monitor power output and cadence using the athlete’s own bike, rather than being restricted to a laboratory-based ergometer. Until recently, pedal-based systems have not provided the same measure of reliability when compared with more traditional crank- or hub-based systems, with Sparks et al. suggesting that the Look Keo power pedals were not as reliable as the SRM Powermeter during an incremental testing protocol. Recently, the reliability and validity of the PowerTap P1 pedals have been investigated between 100 and 500 W at 70, 85, and 100 rpm. These authors reported that the P1 pedals slightly underestimated the SRM Powermeter by 2 to 7 W at 100 W (P = 0.06) and 200 W (P = 0.005). The authors suggested that the P1 pedals were reliable and valid, concluding that they were a cost-effective alternative to laboratory-based ergometers.

It has previously been suggested that reliability and validity studies on power measuring devices are limited to using a single test-retest protocol, with suggestions that reliability may be reduced for older systems. To the authors’ knowledge, the reliability and validity of pedal-based power meters have not been investigated over an extended period, and it is reasonable to suggest that both the reliability and validity of such systems will change over time making monitoring performance changes difficult. Therefore, the aims of this study were to (1) evaluate agreement between the P1 pedals and the Lode Excelsior Sport, (2) evaluate the reliability of the P1 pedals between testing sessions, and (3) compare the reliability and validity of the P1 pedals before and after ~100 h of use.

Methods

Participants

Initial testing (P1b) was completed by 10 male amateur cyclists using a pair of new PowerTap P1 pedal (mean [SD]) age 34.6 [8.8] y, body mass 80.8 [8.8] kg, stature 1.83 [0.05] m. Following a period of 15 months and ~100 h of laboratory use, the testing protocol was repeated (P1a) with an additional 10 cyclists (mean [SD], age 30 [7] y, body mass 80.5 [11.9] kg, stature 1.83 [0.08] m). During each testing period, the protocol was repeated on 2 occasions, separated by a minimum of 48 h. All testing was carried out on an electronically braked cycle ergometer (Excelsior Sport; Lode, Groningen, The Netherlands) with the pedals installed following the manufacturer’s guidelines.

Experimental Procedures

Following a 10-minute warm-up, participants completed four 5-minute submaximal cycling bouts (100, 150, 200, and 250 W) using the ergometer’s hyperbolic mode, each separated by a 5-minute recovery period at 50 W. The participants were then given a 15-minute active recovery period at 100 W before completing a 2-minute maximal time-trial effort against a fixed resistance. Following an additional 15-minute recovery period, participants were required to complete two 10-second maximal sprints, each separated by a 2-minute recovery period. Following a period of 15 months and ~100 h of typical laboratory-based testing using the P1 pedals and the Lode Excelsior Sport, the previously mentioned procedure was repeated. Prior to both testing periods, the Lode Excelsior Sport was calibrated using a dynamic calibration rig (Calibrator 2000; Lode) at 25 to 150 W (60 rpm) and 200 to 500 W (100 rpm).
Statistical Analyses

Data were exported from the Lode Excalibur Sport and PI pedals with the mean power output for each submaximal intensity calculated. For the 10-second sprints, the peak power output from each system was exported for analysis. Comparisons between the Lode Excalibur Sport and the PI pedals were made using a Mann–Whitney U test with agreement assessed using limits of agreement (LOA). Predicted versus residual values for power output were plotted to check for heteroscedasticity. Test-retest reliability was measured using coefficient of variation (CV) and typical error of measurement and upper and lower 95% confidence limits. Using the equation, $n = \frac{r^2}{S_e^2}$, where CV is used for $r$ and a smallest worthwhile change of 0.2 is used for $d$, the estimated sample size for a test-retest study design was also calculated.8 Using the example described by Kirkland et al.,10 the smallest worthwhile change was calculated from the data published by Folkland et al.,11 where the mean power output during a 16.1-km time trial was 227 W, with a SD of 15 W (Table 1). Statistical significance was set to $P = 0.05$, with all data reported as mean (SD).

Results

A Mann-Whitney U test identified significant differences between the Lode Excalibur Sport and the PI pedals at 100 W [100.0 (0.0) W vs 100.4 (2.2) W, $P = 0.006$]; 150 W [150.0 (0.0) W vs 151.2 (2.1) W, $P = 0.006$]; 200 W [200.0 (0.0) W vs 206.6 (2.5) W, $P = 0.005$]; and 250 W [250.0 (0.0) W vs 251.7 (2.1) W, $P = 0.006$]. Significant differences were also seen during the all-out sprints (96.7 [111.0] W vs 105.4 [116.2] W, $P = 0.005$, 95% LOA of –40 to 54 W). No significant differences between the Lode Excalibur Sport and PI pedals were observed during the 2-minute all-out time trial (402.7 [37.1] W vs 398.9 [54.8] W, $P = 0.718$, 95% LOA of 4 to 18 W) (Figure 1).

Following 100 hours of use, a Mann-Whitney U test showed no significant differences between the Lode Excalibur Sport and the PI pedals at 100 W [100.0 (0.0) W vs 100.2 (1.9) W, $P = 0.799$]; 150 W [150.0 (0.0) W vs 149.0 (2.0) W, $P = 0.853$]; 200 W [200.0 (0.0) W vs 199.3 (2.6) W, $P = 0.289$]; and 250 W [250.0 (0.0) W vs 249.2 (3.1) W, $P = 0.289$]. Furthermore, no significant differences between the Lode Excalibur Sport and the PI pedals were seen during the 2-minute all-out time trial (75.7 [45.0] W vs 73.7 [40.2] W, $P = 0.983$, 95% LOA of 17 W) or during the all-out sprints (70.9 [132.6] W vs 93.6 [169.5], $P = 0.412$, 95% LOA of 43 to 245 W) (Figure 1).

The CV and typical error of measurement for the PI and PI pedals during submaximal cycling bouts, the 2-minute all-out time trial, and all-out sprints are presented in Table 1.

<table>
<thead>
<tr>
<th>PowerTap PI16</th>
<th>PowerTap PI160</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV, %</td>
<td>TEM, W</td>
</tr>
<tr>
<td>100 W</td>
<td>0.6 (0.2–1.0)</td>
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<tr>
<td>150 W</td>
<td>0.7 (0.5–1.0)</td>
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<tr>
<td>200 W</td>
<td>0.7 (0.5–1.1)</td>
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<tr>
<td>250 W</td>
<td>0.6 (0.4–1.2)</td>
</tr>
<tr>
<td>All-out sprints</td>
<td>1.3 (0.4–2.2)</td>
</tr>
</tbody>
</table>

**Table 1** Estimated Sample Sizes Required for a Test–Re test Study Design, CV, and Absolute TEM Between Testing Sessions 1 and 2 (Including 95% Confidence Limits)

**Discussion**

The results of this study suggest that the PowerTap PI pedals provide reliable data during submaximal cycling and that reliability is maintained after 100 hours of laboratory use. During all-out sprint performance, the PI pedals appeared to underestimate power output by approximately 60 W when first tested and underestimate power output by approximately 40 W after prolonged use. Figure 2 highlights the heteroscedastic nature of power output data recorded by the PI pedals, with an increase of error observed at higher power outputs. It is possible that the location of the strain gauges used by each system may help to explain these differences. The strain gauges in the PI pedals are housed within the pedaling body, whereas the Lode Excalibur Sport has strain gauges mounted on the crank, and therefore, some force may dissipate through the pedal before being measured at the crank.12

The CV of the PI pedals (0.5–2.0%) during the submaximal interval is comparable, but slightly lower than a recent study by Pallante and Llorente13 who concluded that the PI pedals produced a CV of 2.4% to 3.7% when cycling at 70 to 100 rpm. The results of this study are also comparable with alternative systems, with Bernardi et al.14 reporting the SRM Powermeter to have a CV of 0.2% to 2.1% at submaximal intensities and the PowerTap (but) CV of 0.9% to 2.6%, between testing sessions. According to Hopkins,15 the CV in sports science reliability testing should not exceed 5%, and in this study, the new and unused PI pedals met this criteria for all tested power outputs. However, after a period of 100 hours of use, the CV observed during the all-out sprint performance increased slightly above this recommendation to 6.3%.

The results of this study would suggest that although not valid when initially purchased, the PI pedals provide valid data after prolonged use when compared with the Lode Excalibur Sport. During the initial period of testing, a significant difference was seen for all power outputs between 100 and 250 W; however, no significant differences were seen during repeat testing. Despite the significant differences observed during the initial period of testing, the actual mean percentage differences were less than 1% for all submaximal power outputs. Table 1 highlights that some care should be taken if using the PI pedals during a sprint-based test-retest study design, with a substantially greater sample size required, when compared with submaximal power outputs. This study compared the PI pedals with the Lode Excalibur Sport at a limited selection of power outputs, and although they were typical of those at which amateur cyclists train and race, the fact that a full range of power outputs was not compared is a limitation.

(Ahead of Print)
PowerTap P1 Reliability and Validity

Figure 1 — Bland-Altman plots showing the LoA between (A) Lode Eclipsor Sport and P1 pedals during a 2-minute time trial, (B) Lode Eclipsor Sport and P1100 pedals during a 2-minute time trial, (C) Lode Eclipsor Sport and P1 pedals during a 10-second all-out sprint, and (D) Lode Eclipsor Sport and P1100 pedals during a 10-second all-out sprint. The solid line represents the mean difference in power output, and the dashed line represents the 95% LoA. LoA indicates limits of agreement.

Figure 2 — Plot of predicted versus residual (Lode−P1) values for P1 pedals (open circles) and P1100 pedals (closed circles).

It is recommended that future studies investigate the reliability and validity of the P1 pedals between 500 and 700 W.

Reliability studies are common within sports science when assessing new testing equipment; however, the majority use simple test–retest study designs, separated by several days. For researchers...
to have confidence in their results, it is essential that the equipment used during data collection demonstrates reliability across the relevant period of assessment, for example, before and after a 12-week training study. Future studies should utilize a more robust study design such as the one presented in this study when assessing the reliability of testing equipment.

**Conclusion**

The results of this study suggest that PowerTap P1 pedals have acceptable test–retest reliability for amateur cyclists, which is maintained after prolonged use. The P1 pedals were significantly different to the Lode Excalibur Sport during sub-maximal cycling in early use; however, no significant differences were seen when repeated, and power output was within 1% of the Lode Excalibur Sport before and after ~160 hours of use during sub-maximal power outputs.

**Acknowledgments**

The authors would like to thank Dr. Helen Thomas and Dr. Michelle Jones for their assistance during this study. The authors would also like to thank all the participants who volunteered their time to take part in this study.

**References**


APPENDIX B – CONFERENCE PRESENTATIONS

B.1 World Congress of Cycling Science 2014

The reliability and validity of the 3-minute critical power test

J Wright, S Jobson, and S Bruce-Low

Abstract

Background: Athletes utilise exercise testing to assist with training design and race strategy. Critical power (CP) is a useful addition to an exercise testing battery as it provides an estimate of the heavy-severe exercise domain boundary (Vanhatalo et al., 2007: Medicine & Science in Sports & Exercise, 39(3), 548-55). Although the benefits of calculating CP are known, the traditional CP test protocol is excessively time consuming. Studies have suggested that CP can be obtained from a single 3-minute bout of 'all-out' exercise using the Lode Excalibur Sport cycle ergometer in linear mode (Vanhatalo et al., 2008: Medicine & Science in Sports & Exercise, 40(9), 1560-6). A more recent study (Karsten et al., 2013: International Journal of Sports Medicine, 35(4), 304-9) suggests that the 3-minute test does not provide a valid measure of critical power when using the SRM cycle ergometer in isokinetic mode.

Purpose: To investigate the reliability and validity of the 3-minute critical power test in both isokinetic and linear modes using the Lode Excalibur Sport.

Methods: Six male cyclists (mean ± SD: age 33 ± 7.7 yr, body mass 83.42 ± 9.9 kg, maximum aerobic power (MAP) 343 ± 60 W, VO2max 4.39 ± 0.77 L·min⁻¹) gave written informed consent to participate in this study, which was approved by Southampton Solent University’s ethics committee. Each participant took part in 8 trials, each separated by a minimum of 48 hours. The first trial took part in two stages. The first was an incremental step test (100 W start with 25 W increments every 3 minutes) to calculate gas exchange threshold (GFT). The second stage was a ramp test (100 W start with 20 W·min⁻¹ increments) to calculate MAP and VO2max. During trials 2–4, each participant completed three efforts to exhaustion (80, 100 and 105% MAP). The results from these trials were used to calculate critical power, which included both the first time (CP1) and work-time (CP2) critical power models. Traditionally, these models have both been used to calculate CP. The final four trials were used to estimate critical power from two separate 3-minute protocols. Two trials were carried out using the linear mode following the protocol described by Vanhatalo et al. (2008). The two remaining trials were carried out in the isokinetic mode at the participant’s preferred cadence following the protocol described by Karsten et al. (2013). Apart from trial one, all testing sessions were carried out in a randomized order. A repeated measures ANOVA was used to compare CP and End Power (EP) with significance set at p<0.05. Coefficient of variation was used to compare EP-isokinetic and EP-linear between each testing session. For reliability to be seen in sports science testing it has been suggested that a CV of less than 5% is required (Hopkins, 2000: A new view on statistics. Retrieved 31 March 2014, from http://www.sportsci.org/resource/stats).

Results: There was no significant difference between EP-isokinetic and CP1 (+2.6 W, p=0.80) or between EP-isokinetic and CP2 (+6.1 W, p=0.48). There were significant differences between EP-linear and CP1 (+31.6 W, p=0.01) and between EP-linear and CP2 (+39.2 W, p=0.02). Coefficient of variation in EP-isokinetic and EP-linear was 3.3% and 1.1%, respectively. Discussion: To the authors’ knowledge this is the first time that the linear and isokinetic modes have been evaluated in a single cohort. The results suggest that the 3-minute isokinetic test provides a reliable measure of EP and a valid measure of CP. Although the 3-minute linear test seems to provide a reliable measure of EP, these results suggest that it does not provide a valid measure of CP. Therefore, the results from this pilot study do not fully support previous literature (Vanhatalo et al., 2008; Karsten et al., 2013).

Conclusion: This study provides preliminary evidence to suggest that the 3-minute isokinetic testing protocol can be used to estimate the heavy-severe exercise domain boundary.

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The reliability and validity of the 3-minute critical power test in linear and isokinetic mode

James Wright, Simon Jobson, Stewart Bruce-Low, David Jessop

Abstract

Background: Exercise testing for cyclists provides key information when selecting training and race strategies. Shorter testing protocols are favored by coaches and recently it has been suggested that critical power (CP) and the finite work capacity, $W'$, can be estimated from a single 3-minute bout of 'all-out' exercise using the Lode Excalibur Sport cycle ergometer. These estimates are termed end power (EP) and work above end power (WEP) respectively (Vanhatalo et al., 2007: Medicine & Science in Sports & Exercise, 39(3), 548–55). Considering the physiological basis of this test, it should be possible to accurately estimate CP and $W'$ irrespective of the ergometer used. However, a recent study (Karsten et al., 2013: International Journal of Sports Medicine, 35(4), 304–9) has suggested that although reliable, the 3-minute test in isokinetic mode using an SRM ergometer does not provide a valid measure of CP or $W'$.

Purpose: To investigate the reliability and validity of the 3-minute critical power test in both isokinetic and linear modes using the Lode Excalibur Sport cycle ergometer.

Methods: Twelve male cyclists participated in this study (mean ± SD; age 32 ± 6.60 yr, body mass 81.63 ± 8.57 kg, maximum aerobic power (MAP) 4.39 ± 36.14 W, $\dot{V}O_{\text{max}}$ 4.70 ± 0.59 L min$^{-1}$). Each participant completed 8 trials, with the first carried out to calculate GET (gas exchange threshold), MAP and $\dot{V}O_{\text{max}}$. During trials 2–4, each participant completed three efforts to exhaustion (80, 100 and 105% MAP) in order to calculate CP and $W'$ using both the 1/time (CP1 and W1) and work-time (CP2 and W2) equations. Four additional trials were carried out to estimate CP and $W'$ (EP and WEP) from two different 3-minute protocols (linear and isokinetic modes). A repeated measures ANOVA was used to compare CP with EP and $W'$ with WEP. Significance was set at $p<0.05$. Coefficient of variation was used to compare EP-isokinetic, EP-linear, WEP-isokinetic and WEP-linear between each testing session. The limits of agreement between CP and EP, and $W'$ and WEP were estimated using Bland and Altman plots for each protocol.

Results: A repeated measures ANOVA showed no significant difference between EP-isokinetic and CP1 (+3.4 W, $p=0.38$) or between EP-isokinetic and CP2 (+0.8 W, $p=0.965$). Significant differences were seen between EP-linear and CP1 (+30.9 W, $p=0.004$), EP-linear and CP2 (+35.1 W, $p=0.003$), WEP-isokinetic and W1 (+8.2 kJ, $p<0.000$), WEP-isokinetic and W2 (+10.0 kJ, $p<0.000$), WEP-linear and W1 (+10.4 kJ, $p<0.000$) and between WEP-linear and W2 (+12.2 kJ, $p<0.000$). Coefficient of variation in EP-isokinetic, EP-linear, WEP-isokinetic and WEP-linear was 1.93%, 2.05%, 8.44% and 5.39%, respectively, between trials 1 and 2. For reliability in sports science testing it has been suggested that a CV of less than 5% should be seen (Hopkins, 2000: A new view on statistics. Retrieved 31 March 2014, from http://www.sportsci.org/resource/stats). The limits of agreement between CP and EP, and between $W'$ and WEP for each protocol can be seen in Figures 1 and 2 respectively.

Conclusions: This study suggests that the 3-minute isokinetic test provides a reliable measure of EP and a valid measure of CP. Although the 3-minute linear test seems to provide a reliable measure of EP, these results suggest that it does not provide a valid estimate of CP. Results also suggest that neither the isokinetic or linear mode provide a reliable measure of WEP or a valid measure of $W'$. Therefore, this study suggests that the 3-minute isokinetic test can be used to estimate critical power.
Figure 1. Limits of agreement between EP-isokinetic and CP1 (a), EP-isokinetic and CP2 (b), EP-linear and CP1 (c) and EP-linear and CP2 (d). Solid line represents mean bias. Dashed lines represent the 95% LoA.

Figure 2. Limits of agreement between WEP-isokinetic and W'1 (a), WEP-isokinetic and W'2 (b), WEP-linear and W'2 (c) and WEP-linear and W'2 (d). Solid line represents the mean bias. Dashed lines represent the 95% LoA.

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B.3 British Association of Sports Science Annual Conference 2018

D1.53.56(6). A novel cycling protocol to estimate critical power and the finite work capacity

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Critical power (CP) and the finite work capacity (W) are traditionally calculated from multiple time-to-exhaustion tests performed on separate days. The 3 min all-out cycling test was developed in 2007 and provided a practical alternative to the original and time-consuming testing protocol (Vanhaelen, Doust and Bumley, 2007, Medicine & Science in Sports & Exercise, 39, 548-555). However, some authors have found that the 3 min all-out cycling test significantly overestimates CP (McClave, LedBlanc, and Hawkins, Journal of Strength and Conditioning Research, 25, 3093-3098).

Therefore, the aim of this study was to investigate the validity and reliability of a novel all-out cycling test used to estimate CP and W. This study also investigated the physiological responses to cycling at CP. Following institutional ethics approval, ten participants completed ten tests: 1) an incremental test to exhaustion to calculate gas exchange threshold, maximum aerobic power and peak oxygen uptake; 2–4) three time-to-exhaustion tests performed at 80, 100 and 105% MAP to calculate CP and W from the power-time model \( P = W^{(1/2)} + CP \), 5) a 3 min all-out cycling test to calculate end power (EP\(_{\text{end}}\)) and work done above EP\(_{\text{end}}\) (6–7) two novel all-out cycling tests to calculate CP (EP\(_{\text{max}}\)) and WEP (WEP\(_{\text{max}}\)) and 1–10) three time-to-exhaustion tests at CP calculated from each respective protocol. No significant differences were seen between CP and EP\(_{\text{max}}\) (271 ± 32 W vs 273 ± 19 W, \( P = 0.293, \text{ES} = 0.22 \)) or between CP and EP\(_{\text{min}}\) (271 ± 32 W vs. 281 ± 41 W, \( P = 0.354, \text{ES} = 0.22 \)). However, significant differences were seen between W and WEP\(_{\text{max}}\) (180 ± 13.6 W vs. 14.0 ± 2.5 W, \( P = 0.021, \text{ES} = 0.92 \)) and between W and WEP\(_{\text{min}}\) (180 ± 13.6 W vs. 116 ± 2.8 W, \( P = 0.015, \text{ES} = 1.47 \)). Cycling at CP resulted in a power output which was sustainable for less than 20 min with a mean duration of 19 min 48 s observed from the original CP protocol, 15 min 25 s from the 3 min all-out protocol and 16 min 22 s from the novel all-out protocol. The study concludes that CP can be estimated from a novel all-out cycling test; however, caution should be taken when estimating W. Furthermore, cycling at CP, irrespective of the method of calculation, results in exhaustion occurring within 20 min.

D2.P36. Validity and reliability of the powertap P1 and garmin vector 2 power pedals

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The development of the cycle-mounted power meter has allowed performance (e.g. power output) to be monitored using the athlete’s own bike (Earnest, Wharton, Church and Lucia, 2009, Journal of Strength and Conditioning Research, 19, 344–348). A popular option for amateur cyclists is the pedal-based power meter as they allow the flexibility of transferring between bikes but are also cheaper than the “gold standard” SRM Powermeter. Currently, two of the most common pedal-based power meters are the PowerTap P1 (P1) and Garmin Vector 2 (V2). The aims of this study were to: 1) compare the Lode Excalibur Sport with the P1 and V2 pedals and 2) investigate the test-retest reliability of the P1 and V2 pedals. Following institutional ethics approval, ten participants completed four 5 min sub-maximal cycling bouts (100, 150, 200, and 250 W), a 2 min maximal time-trial and two 10 s maximal sprints. Each participant completed the protocol on four occasions, two using the P1 pedals and two using the V2 pedals. Significant differences were seen between the Lode Excalibur Sport and the P1 pedals at 100 W (100.0 ± 0.0 vs. 100.4 ± 3.8, \( P = 0.006 \), 150 W (150.0 ± 0.0 vs. 151.2 ± 2.7, \( P = 0.006 \)), 200 W (200.0 ± 0.0 vs. 201.6 ± 2.5, \( P = 0.001 \)), 250 W (250.0 ± 0.0 vs. 252.2 ± 2.6, \( P = 0.006 \)) and during the all-out sprints (962.7 ± 11.0 vs. 1026.4 ± 11.6, \( P = 0.020, \text{ES} = 0.53 \)). Significant differences were also seen between the Lode Excalibur Sport and the V2 pedals at 100 W (100.0 ± 0.0 vs. 104.6 ± 4.2, \( P < 0.001 \)), 150 W (150.0 ± 0.0 vs. 156.3 ± 4.9, \( P < 0.001 \)), 200 W (200.0 ± 0.0 vs. 207.2 ± 6.0, \( P = 0.001 \)), 250 W (250.0 ± 0.0 vs. 261.4 ± 7.2, \( P < 0.001 \)) and during the all-out sprints (973.9 ± 100.5 vs. 1026.1 ± 95.3, \( P = 0.018, \text{ES} = 0.53 \)). However, no significant differences were seen during the 2 min time-trial between the Lode Excalibur Sport and the P1 pedals (402.7 ± 51.7 vs. 398.8 ± 54.8, \( P = 0.718, \text{ES} = 0.07 \)) or the V2 pedals (401.9 ± 46.2 vs. 402.2 ± 48.4, \( P = 0.799, \text{ES} = 0.03 \)). The coefficient of variation for the P1 and V2 pedals ranged from 0.57–1.28% and 0.73–2.7%, respectively, during the sub-maximal cycling bouts. These results suggest that some care should be taken when using the P1 and V2 pedals during sprint performance. Results also suggest that during sub-maximal power outputs, both the P1 and V2 pedals are reliable.
APPENDIX C – HEALTH & SAFETY AND ETHICS CONSIDERATIONS

C.1 Participant Information Sheet – Study 1

Title of the Study: The Reliability and Validity of the Cycling 3-min Critical Power Protocol.

Thank you for expressing an interest in this project. Please read the following information sheet carefully before deciding whether to participate in the project. If you choose to participate in the project, we thank you. As a participant, prior to taking part in any testing, you will be required to:

1. Carefully read this Information Sheet that will outline the procedures and the potential risks to yourself.
2. Complete and sign a Consent Form.
3. Complete and sign a Physical Activity Readiness Questionnaire (PAR-Q).

1. What are the aims of the project?
The aim of this project is to evaluate two different protocols for calculating critical power during cycling.

2. What type of participants does the project require?
Participants in the project will be healthy, active males between the ages of 18 and 50 years (inclusive). Participants should have no physical injury or impairment that might stop them from completing repeated bouts of submaximal and maximal cycling exercise.

3. How many times will I have to visit the laboratory?
Each experiment will require visiting the laboratory on eight occasions over a period of not more than 30 days. It is very important that you can attend all sessions and, therefore, please take this into consideration before expressing an interest in taking part. Although the first visit of each experiment will take approximately 2 hours, the following sessions are very short (approximately 30 minutes).

Visit 1 – Determination of Lactate Threshold, VO$_{2\text{max}}$ and MAP (maximal aerobic power)
Visit 2 – Maximal ‘all-out’ effort at 80 % MAP
Visit 3 – Maximal ‘all-out’ effort at 100 % MAP
Visit 4 – Maximal ‘all-out’ effort at 105 % MAP
Visit 5 – Maximal ‘all-out’ 3-minute cycling test a linear factor mode
Visit 6 – Maximal ‘all-out’ 3-minute cycling test an isokinetic mode
Visit 7 – Maximal ‘all-out’ 3-minute cycling test a linear factor mode
Visit 8 – Maximal ‘all-out’ 3-minutes cycling test an isokinetic mode

Apart from visit 1, all other sessions will be carried out in a randomly assigned order.

4. What will the participants be asked to do?
Visit 1: Determination of Lactate Threshold, VO$_{2\text{max}}$ and MAP
You will be required to perform an incremental cycling test to exhaustion to determine lactate threshold and VO$_{2\text{max}}$. Following a self-selected warm up for 10 minutes, you will start cycling at a power output of 150 W with increments of 25 W occurring at the end of each 3-minute stage. Heart rate and a capillary blood lactate sample will be taken in the last 10 seconds of each stage. Throughout the test you will be required to breathe through a face mask (this does not restrict your breathing). Once your lactate threshold has been established you will be given a 30-minute period of rest.

The VO$_{2\text{max}}$ test will commence at a work rate of 150 W with increments of 5 W every 15 seconds. During this test you will be instructed to continue cycling until volition exhaustion. Once again you will be required to breathe through a face mask for the duration of the test. This is a very demanding test and strong verbal encouragement will be given throughout. On completion of this test a final capillary blood lactate sample will be taken.

Visits 2-8: Critical Power Protocol
Critical power will be determined from three trials of maximal exercise lasting with each lasting less than 20 minutes and will take place on 6 separate days with a minimum of 24 hours between them. Each trial will be completed on two occasions in a randomly assigned order (refer to point 3 above). Before each maximal trial you will be given the chance to perform a standardised warm up for 10 minute. Following the warm up, you will be instructed to cycling ‘all-out’ for the duration of each trial. During each effort you should not pace yourselves and peak power output should be attained in the first 10 seconds. The SRM bike will be set in an isokinetic mode in order to set the resistance and allow you to maintain your preferred cadence throughout each trial. Strong verbal encouragement will be given throughout the duration of each trial. Breath by breath expired air (using a face mask) and heart rate will be recorded throughout each trial. A capillary blood sample will be taken at rest and immediately after each trial.

5. What are the potential risks and discomforts of the project?
There is a small risk that participants could become injured whilst performing each cycling or running test. The risk of this occurring will be minimised by consulting the Schedules of Approved Procedures (SAP Phys2 and Phys4 - available on request) and by operating according to the guidelines set by the British Association of Sport and Exercise Sciences. The participants recruited for this study are required to be active and to be accustomed to performing high intensity exercise. Therefore, the risk of injury within the testing sessions is not deemed to be greater than the risk of injury encountered in participants’ normal physical activities.

Participants will be given the opportunity to perform an adequate warm-up and warm-down before and after each test. Any potential health and safety risks will be minimised through good practise and adherence to professional codes of conduct. There will be a first aider present throughout all testing. Participants will be monitored throughout the testing and for at least 15 minutes afterwards to ensure participant well-being.

6. Can participants change their mind and withdraw from the project?
Individuals may withdraw from participation in the project at any time and without any disadvantage of any kind.

Please contact us if you have any questions
James Wright, PhD Research Student
Email: james.wright@solent.ac.uk
Professor Simon Jobson, Director of Studies
Email: simon.jobson@winchester.ac.uk
Study Title: The Effect of Cadence on the 3-minute Critical Power Test

Invitation to participate
You have been invited to take part in a research study. Prior to your agreement to take part it is important that you understand the specific nature of the research and what will be required of you during the study. Please take time to read the following information carefully and be certain to ask if there is anything that remains unclear to you. Please take time to decide whether you wish to take part, or not. You are free to discuss your choice with friends, family or your GP. After receipt of this information sheet, and having read and understood it, we ask that you respond within a period of one week as to your intent to participate.

Do I have to take part?
The decision to take part is entirely your own. Should you wish to take part you will be required to sign a participant consent form. Nonetheless, upon deciding to take part you will remain free to withdraw from the investigation at any point. If you make the decision to withdraw, this will not affect your relationship with the research team or any other individuals involved with their organisation.

What are the aims of the project?
The aim of this project is to measure the effect of cadence on the 3-minute critical power protocol.

Why have I been invited to participate?
To investigate the research question, we are looking to recruit male cyclists between the ages of 18 and 49 (inclusive) who do not have any physical injury or impairment. Volunteers should be accustomed to completing repeated bouts of maximal cycling during training and or racing.

How many times will I have to visit the laboratory?
Each experiment will require visiting the laboratory on eight occasions over a period of not more than 30 days. It is very important that you can attend all sessions and therefore please take this into consideration before expressing an interest in taking part. Although the first visit of each experiment will take approximately 1 hour, the following sessions should be completed within 30 minutes.

Visit 1 – Determination of Gas Exchange Threshold, VO_{2max} and MAP (maximal aerobic power)
Visit 2 – Maximal ‘all-out’ effort at 80 % MAP
Visit 3 – Maximal ‘all-out’ effort at 100 % MAP
Visit 4 – Maximal ‘all-out’ effort at 105 % MAP
Visit 5 – Maximal ‘all-out’ 3-minute cycling test (preferred cadence)
Visit 6 – Maximal ‘all-out’ 3-minute cycling test (preferred cadence –5 rpm)
Visit 7 – Maximal ‘all-out’ 3-minute cycling test (preferred cadence +5 rpm)
Visit 8 – Maximal ‘all-out’ 3-minute cycling test (preferred cadence +10 rpm)
Apart from visit 1, all other sessions will be carried out in a randomly assigned order.

**What will be required from you?**

**Visit 1: Determination of Gas Exchange Threshold, \( VO_{2\text{peak}} \) and MAP**

Prior to this test, several resting checks will be carried out (blood pressure, resting 12-lead ECG and a health questionnaire). The \( VO_{2\text{max}} \) test will commence at a work rate of 150 W with increments of 5 W every 15 seconds. During this test you will be instructed to continue cycling until volition exhaustion. Throughout the test you will be required to breathe through a face mask (this does not restrict your breathing). This is a very demanding test and strong verbal encouragement will be given throughout. On completion of this test a capillary blood lactate sample will be taken.

**Visits 2-8: Critical Power Protocol**

The first method for calculating critical power will be from three separate maximal trials to exhaustion at 80, 100 and 105% MAP, with each trial separated by at least 48 hours. Before all trials you will be given the chance to perform a standardised warm up for 10 minutes. The second method for calculating critical power will be from three separate 3-minute 'all-out' efforts. This is not a paced 3-minute test and you should aim to hit peak power (and cadence) within the first 10 seconds. Each test will be carried out at a slightly different resistance which will be determined by your preferred cadence. Breath-by-breath expired air (using a face mask) and heart rate will be recorded throughout each trial. A capillary blood sample will be taken at rest and immediately after each trial.

**What are the advantages of taking part?**

1. You will receive a series of comprehensive health and fitness tests that we hope will provide informative data.
2. You will experience what it is like to participate in testing within a laboratory environment.
3. You will be provided with training advice if required.

**What are the potential disadvantages of taking part?**

1. Completing maximal exercise can be tiring, requiring a substantial amount of motivation and energy. You are likely to feel fatigued after each test, however you should fully recover within 24 hours depending on your training status.
2. There is a small risk that participants could become injured whilst performing each cycling test but this risk will be minimised by operating according to the guidelines set by the British Association of Sport and Exercise Sciences. There will be a first aider present throughout all testing and participants will be monitored throughout the testing and for at least 15 minute afterwards to ensure participant well-being.
3. Whenever people exercise maximally there is a very small risk of more serious conditions, including heart problems. The chance of this occurring is estimated to be 1 in 33,000.

**Confidentiality**

All information which is collected about you during the research will be kept strictly confidential. Any information which leaves the university will have your name removed so that you cannot be recognised. It will not be possible to identify you in any publication of the study.

**Who has reviewed the study?**

Prior to any data being collected the study has been reviewed and approved by the ethics committee of the Centre of Health, Exercise and Sport Science at Southampton Solent University.
What if I wish to make a complaint?
Any complaint about the way you have been dealt with during the study will be addressed seriously. You may register any complaints you might have about this experiment to the Head of Research and Innovation at Southampton Solent University (023 8201 6457). You will be offered the opportunity to provide feedback on the experiment using standard report forms. In the event that something does go wrong and you are harmed during the research and this is due to someone’s negligence then you may have grounds for a legal action for compensation against Southampton Solent University but you may have to pay your legal costs.

Please contact us if you have any questions
James Wright, PhD Research Student  
Email: james.wright@solent.ac.uk  
Professor Simon Jobson, Director of Studies  
Email: simon.jobson@winchester.ac.uk
Study Title: Validity and Reliability of the Garmin Vector 2 and PowerTap P1 pedals

Invitation to participate
You have been invited to take part in a research study. Prior to your agreement to take part it is important that you understand the specific nature of the research and what will be required of you during the study. Please take time to read the following information carefully and be certain to ask if there is anything that remains unclear to you. Please take time to decide whether you wish to take part, or not. You are free to discuss your choice with friends, family or your GP. After receipt of this information sheet, and having read and understood it, we ask that you respond within a period of one week as to your intent to participate.

Do I have to take part?
The decision to take part is entirely your own. Should you wish to take part you will be required to sign a participant consent form. Nonetheless, upon deciding to take part you will remain free to withdraw from the investigation at any point. If you make the decision to withdraw, this will not affect your relationship with the research team or any other individuals involved with their organisation.

What are the aims of the project?
The aim of this project is to investigate the validity and reliability of two commonly used cycling power pedals.

Why have I been invited to participate?
To investigate the research question, we are looking to recruit male cyclists between the ages of 18 and 49 (inclusive) who do not have any physical injury or impairment. Volunteers should be accustomed to completing repeated bouts of maximal cycling during training and or racing.

How many times will I have to visit the laboratory?
You will be required to visit the laboratory on four occasions over a period of not more than 14 days. It is very important that you can attend all sessions and therefore please take this into consideration before expressing an interest in taking part. Testing sessions are likely to last between 50–70 minutes.

What will be required from you?
Prior to each test, several resting checks will be carried out (blood pressure and a health questionnaire). You will then be required to complete a sub-maximal protocol, a 2-min maximal time trial effort and two 10 second sprints:

- 5 minute cycling at 100, 150, 200 and 250 W with 5 minute recovery between each interval
- 10-15 minute recovery
- 2 minute maximum time trial effort
- 10 minute recovery
- 2 x 10 second sprints separated by 2 minute recovery

The above protocol will take place on four occasions, twice using the Garmin Vector Pedals and twice using the PowerTap P1 pedals.

What are the advantages of taking part?
1. You will receive a series of comprehensive health and fitness tests that we hope will provide informative data.
2. You will experience what it is like to participate in testing within a laboratory environment.
3. You will be provided with training advice if required.

What are the potential disadvantages of taking part?
1. Completing maximal exercise can be tiring, requiring a substantial amount of motivation and energy. You are likely to feel fatigued after each test, however you should fully recover within 24 hours depending on your training status.
2. There is a small risk that participants could become injured whilst performing each cycling test, but this risk will be minimised by operating according to the guidelines set by the British Association of Sport and Exercise Sciences. There will be a first aider present throughout all testing and participants will be monitored throughout the testing and for at least 15 minutes afterwards to ensure participant well-being.
3. Whenever people exercise maximally there is a very small risk of more serious conditions, including heart problems. The chance of this occurring is estimated to be 1 in 33,000.

Confidentiality
All information which is collected about you during the research will be kept strictly confidential. Any information which leaves the university will have your name removed so that you cannot be recognised. It will not be possible to identify you in any publication of the study.

Who has reviewed the study?
Prior to any data being collected the study has been reviewed and approved by the ethics committee of the Centre of Health, Exercise and Sport Science at Southampton Solent University.

What if I wish to make a complaint?
Any complaint about the way you have been dealt with during the study will be addressed seriously. You may register any complaints you might have about this experiment to the Head of Research and Innovation at Southampton Solent University (023 8201 6457). You will be offered the opportunity to provide feedback on the experiment using standard report forms. In the event that something does go wrong, and you are harmed during the research and this is due to someone’s negligence then you may have grounds for a legal action for compensation against Southampton Solent University but you may have to pay your legal costs.

Please contact us if you have any questions
James Wright  
PhD Research Student  
Email: james.wright@solent.ac.uk

Dr Helen Thomas  
Director of Studies  
Email: helen.thomas@winchester.ac.uk
**Study Title:** Longitudinal reliability and validity of the Power Tap pedals power meter during sub-maximal and sprint efforts.

**Invitation to participate**
You have been invited to take part in a research study. Prior to your agreement to take part it is important that you understand the specific nature of the research and what will be required of you during the study. Please take time to read the following information carefully and be certain to ask if there is anything that remains unclear to you. Please take time to decide whether you wish to take part, or not. You are free to discuss your choice with friends, family or your GP. After receipt of this information sheet, and having read and understood it, we ask that you respond within a period of one week as to your intent to participate.

**Do I have to take part?**
The decision to take part is entirely your own. Should you wish to take part you will be required to sign a participant consent form. Nonetheless, upon deciding to take part you will remain free to withdraw from the investigation at any point. If you make the decision to withdraw, this will not affect your relationship with the research team or any other individuals involved with their organisation.

**What is the purpose of the study?**
The purpose of the study is to investigate if the agreement of a LIMITS cycling power meter is to an acceptable standard with an SRM power meter. The LIMITS power meter is an affordable and easily transferred power meter that claims an accuracy to within ± 2%. This accuracy is not scientifically tested. SRM is recognised as the gold standard power meter however it is expensive and difficult to transfer among bikes due to being brand specific and mechanically time consuming. If the LIMITS is found to be of an acceptable level of agreement, users with multiple bikes and a lower budget range will have access to an accurate power meter.

**Why have I been invited to participate?**
You have been invited as you are a male aged between 18 and 50 years, with ≥ 2 years cycling experience and fit into a purposive sample for this study.

**How many times will I have to visit the laboratory?**
You will be required to visit the laboratory on four occasions over a period of not more than 14 days. It is very important that you can attend all sessions and therefore please take this into consideration before expressing an interest in taking part. Testing sessions are likely to last between 50–70 minutes.

**What will be required from you?**
Prior to each test, several resting checks will be carried out (blood pressure and a health questionnaire). You will then be required to complete a sub-maximal protocol, a 2-min maximal time trial effort and two 10 second sprints:
- 5 minute cycling at 100, 150, 200 and 250 W with 5 minute recovery between each interval
- 10-15 minute recovery
- 2 minute maximum time trial effort
- 1 minute recovery
- 2 x 10 second sprints separated by 2 minute recovery

What are the advantages of taking part?
You will receive a series of comprehensive health and fitness tests that we hope will provide informative data.
You will experience what it is like to participate in testing within a laboratory environment.
You will be provided with training advice if required.

What are the potential disadvantages of taking part?
Completing maximal exercise can be tiring, requiring a substantial amount of motivation and energy. You are likely to feel fatigued after each test, however you should fully recover within 24 hours depending on your training status.
There is a small risk that participants could become injured whilst performing each cycling test, but this risk will be minimised by operating according to the guidelines set by the British Association of Sport and Exercise Sciences. There will be a first aider present throughout all testing and participants will be monitored throughout the testing and for at least 15 minutes afterwards to ensure participant well-being.
Whenever people exercise maximally there is a very small risk of more serious conditions, including heart problems. The chance of this occurring is estimated to be 1 in 33,000.

Confidentiality
All information which is collected about you during the research will be kept strictly confidential. Any information which leaves the university will have your name removed so that you cannot be recognised. It will not be possible to identify you in any publication of the study.

Who has reviewed the study?
Prior to any data being collected the study has been reviewed and approved by the ethics committee of the Centre of Health, Exercise and Sport Science at Southampton Solent University.

What if I wish to make a complaint?
Any complaint about the way you have been dealt with during the study will be addressed seriously. You may register any complaints you might have about this experiment to the Head of Research and Innovation at Southampton Solent University (023 8201 6457). You will be offered the opportunity to provide feedback on the experiment using standard report forms.
In the event that something does go wrong, and you are harmed during the research and this is due to someone’s negligence then you may have grounds for a legal action for compensation against Southampton Solent University but you may have to pay your legal costs.

Please contact us if you have any questions
Tom Walker
BSc Applied Sport Science Student
Email: 2walkt25@solent.ac.uk

James Wright
Technician Instructor
Email: james.wright@solent.ac.uk
Study Title: Critical power – a novel single test protocol

Invitation to participate
You have been invited to take part in a research study. Prior to your agreement to take part it is important that you understand the specific nature of the research and what will be required of you during the study. Please take time to read the following information carefully and be certain to ask if there is anything that remains unclear to you. Please take time to decide whether you wish to take part, or not. You are free to discuss your choice with friends, family or your GP.

Do I have to take part?
The decision to take part is entirely your own. Should you wish to take part you will be required to sign a participant consent form. Nonetheless, upon deciding to take part you will remain free to withdraw from the investigation at any point. If you make the decision to withdraw, this will not affect your relationship with the research team or any other individuals involved with their organisation.

What are the aims of the project?
The main aim of the project is to investigate the accuracy and reliability of estimating critical power from a novel single test protocol.

Why have I been invited to participate?
In order to investigate the research question, we are looking to recruit male cyclists between the ages of 18 and 49 (inclusive) who do not have any physical injury or impairment. Volunteers should be accustomed to completing repeated bouts of maximal cycling during training and/or racing.

How many times will I have to visit the laboratory?
Each experiment will require visiting the laboratory on ten occasions over a period of not more than 35 days. It is very important that you can attend all sessions and therefore please take this into consideration before expressing an interest in taking part. Although visit one and ten will take approximately 1 hour, all other testing sessions should be completed within 30 minutes:

- Visit 1: Determination of $\dot{V}O_{2\text{max}}$ and maximum aerobic power (MAP)
- Visits 2–4: Maximal efforts at 80, 100 and 105% MAP
- Visit 5: 3-minute ‘all-out’ cycling test protocol
- Visit 6–7: Novel critical power protocol
- Visit 8–10: Time trial at critical power calculated from original, 3-minute and novel testing protocols
What will be required from you?

Visit 1: Determination of Gas Exchange Threshold, $\dot{V}O_{2\text{peak}}$ and MAP
Prior to this test, several resting checks will be carried out (e.g. blood pressure – photo 1) and a health questionnaire will be completed. The $\dot{V}O_{2\text{max}}$ test will commence at a work rate of 150 W with increments of 5 W every 15 seconds. During this test, you will be instructed to continue cycling until volition exhaustion.

Visits 2–4: Traditional critical power protocol
Critical power will be calculated from three separate maximal tests to exhaustion, with each test separated by at least 48 hours. During each test, you will be asked to cycle for as long as possible at a power output which corresponds to 80, 100 and 105% of your MAP.

Visits 5: 3-minute ‘all-out’ cycling test protocol
Critical power will be calculated from a single 3-minute ‘all-out’ cycling test. This is not a paced 3 minute test and you should aim to hit peak power (and cadence) within the first 10 seconds. Each test will be carried out at a fixed resistance which will be determined from visit 1.

Visits 6–7: Novel critical power protocol
Critical power will be calculated from a single test to exhaustion. You will be asked to cycle at 110% MAP until your cadence drops to zero. The bike setting will then be changed to isokinetic mode and you will be instructed to cycle at your highest possible power output for a further 2 minutes.

Visits 8–10: Time trials
You will be asked to complete a time trial corresponding to the critical power calculated from each of the above testing protocols (traditional, 3-minute and novel)

Prior to all testing sessions you will be given the chance to perform a standardised warm up for 10 minutes at 100 W. Throughout each test you will be required to breathe through a face mask (photo 2 - this does not restrict your breathing). A pre- and post-capillary blood lactate sample will be taken for all testing sessions (photo 3). All tests are very demanding and strong verbal encouragement will be given throughout.

What are the advantages of taking part?
1. You will receive a series of comprehensive health and fitness tests that we hope will provide informative data.
2. You will experience what it is like to participate in testing within a laboratory environment.
3. You will be provided with training advice if required.
What are the potential disadvantages of taking part?
1. Completing maximal exercise can be tiring, requiring a substantial amount of motivation and energy. You are likely to feel fatigued after each test, however you should fully recover within 24 hours depending on your training status.
2. There is a small risk that participants could become injured whilst performing each cycling test, but this risk will be minimised by operating according to the guidelines set by the British Association of Sport and Exercise Sciences. There will be a first aider present throughout all testing and participants will be monitored throughout the testing and for at least 15 minutes afterwards to ensure participant well-being.
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Confidentiality
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Who has reviewed the study?
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What if I wish to make a complaint?
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Please contact us if you have any questions
James Wright, PhD Research Student
Email: james.wright@solent.ac.uk

Dr Helen Thomas, Director of Studies
Email: helen.thomas@solent.ac.uk
Informed Consent for Laboratory Based Experimentation

Name of experiment ____________________________________________________________

1. I can confirm that the full details of the experiments/investigations have been explained to me and I have read and understand the relevant participant information sheet (PIS). I am clear about what will be involved, and I am aware of the purpose, the potential benefits and the potential risks. I can also confirm that I have had the opportunity to ask questions that I have about the experiment/investigation procedure.

2. I recognise that I have the right to withdraw my involvement at any time during the testing procedure.

3. Any data collected and stored on a computer will remain anonymous, however I understand that complete anonymity cannot be safeguarded due to the public nature of laboratory sessions.

4. I have completed a health questionnaire and agree to take part in this study.

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<tr>
<th>Name of Participant</th>
<th>Participants Signature</th>
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Declaration by the Academic Investigator/Project Officer

I can confirm that I have provided detailed information about the procedure which the above participant has consented to.

<table>
<thead>
<tr>
<th>Name of Staff</th>
<th>Staff Signature</th>
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Physical Activity Readiness Questionnaire

All information provided will remain confidential

Name.................................................................................................................................

Date of Birth...................................................... Age............. B.P............................mmHg

Are you currently a smoker? Yes/No
Are you a previous smoker? Yes/No

Do you drink alcoholic drinks? Yes/No
If yes do you have: the occasional drink? Yes/No
    a drink every day? Yes/No
    more than one drink a day? Yes/No

Do you suffer, or have you suffered from?
    Asthma (within 2 years)? Yes/No
    Diabetes? Yes/No
    Bronchitis? Yes/No
    Epilepsy? Yes/No
    Any form of heart complaint? Yes/No
    Dizziness or fainting? Yes/No

How would you describe your current level of fitness?
    Unfit/moderately fit/trained

Is there any history of heart disease in your family?
    Yes/No – If yes give details

Do you currently have any form of muscle or joint injury that may be aggravated by the testing?
    Yes/No – If yes give details

Have you had any cause to suspend normal activity in the last two weeks?
    Yes/No – If yes give details

Are you currently taking any form of medication?
    Yes/No – If yes give details
If you answered yes to the question above, have you ever been told that you would not take part in
exhaustive exercise when taking this medication?
Yes/No – If yes give details

In the past month, have you had chest pain when you were not doing physical activity?
Yes/No – If yes give details

Do you feel pain in your chest when you do physical activity?
Yes/No – If yes give details

Have you had hyper/hypothermia, heat exhaustion, or any other heat or cold disorder?
Yes/No – If yes give details

Have you had anaphylactic shock symptoms to needles, probes or other medical-type equipment?
Yes/No – If yes give details

Have you had chronic or acute symptoms of gastrointestinal bacterial infections (e.g. Dysentery, Salmonella)?
Yes/No – If yes give details

Do you have a history of infectious diseases (e.g. HIV, Hepatitis B); and if appropriate to the
experimental design, have a known history of rectal bleeding, anal fissures, haemorrhoids, or any
other condition of the rectum?
Yes/No – If yes give details

Do you have any allergies to plasters, micropore tape, skin electrodes or latex gloves?
Yes/No – If yes give details

Finally, do you know of any other reason that may prevent you from participating in physical activity?
Yes/No – If yes give details

Please supply a name and contact number of a person we can contact in the event of an emergency

Name ________________________________  Telephone number ________________

Participant’s Signature ____________________  Date ____________________

Staff Signature ____________________________  Date ____________________