# THE APPLICATION OF THE CRITICAL POWER CONSTRUCT TO ENDURANCE EXERCISE

KERRY MCGAWLEY

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# Abstract

Critical power (CP) is a theoretical construct reflecting the highest work rate that can be maintained by continuous aerobic energy resynthesis for an infinite period of time. In practice, however, the CP estimate derived from mathematical modelling usually leads to exhaustion within 1 h. While previous research has used traditional measures of aerobic fitness to validate CP, there is disagreement in the literature as to whether CP reflects a physiological steady or a non-steady state. Furthermore, the practical applications of the CP construct have received limited research attention. Therefore, the purpose of this thesis was to clarify the applicability of CP to endurance exercise.

Following experimentation for measurement reliability and equipment validation (chapter 6 and section 9.2, respectively), two experimental studies formed the core of the thesis work. In the first of these two studies (chapter 7), participants were grouped by their peak aerobic power ($\dot{V}O_{2peak}$) as either low (LOW: 26.8 – 40.6 mL·kg$^{-1}$·min$^{-1}$, n = 9), moderate (MOD: 43.6 – 49.6 mL·kg$^{-1}$·min$^{-1}$, n = 8) or high (HIGH: 57.8 – 69.0 mL·kg$^{-1}$·min$^{-1}$, n = 8) fitness. The relationships between CP and traditional measures of aerobic fitness (e.g., lactate threshold, $\dot{V}O_{2peak}$ and maximal minute power) were found to be similar for all fitness groups. Furthermore, $\dot{V}O_2$, blood lactate concentration and heart rate continued to rise over time during exercise at CP for all groups.

In the second main study (chapter 9), recreationally active participants were randomly assigned to groups that trained for six weeks either below CP (<CP, n = 14), at CP (CP, n = 15) or intermittently around CP (CP$_{INT}$, n = 14). Total work was matched between groups and training time was significantly shorter for the CP group compared with the <CP and CP$_{INT}$ groups. While all training interventions resulted in significant increases in CP and other measures of aerobic fitness (e.g., lactate threshold, economy, $\dot{V}O_{2peak}$ and muscle enzyme content), there were no interaction effects between groups. In summary, CP was shown to reflect an unstable physiological state, irrespective of fitness status, that is responsive to continuous and intermittent training and may be used as a time-efficient training intensity improving aerobic fitness.

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## Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Signed: K McGawley

Dated: 30-09-10

In loving memory of Grandma Anne, Grandad Tony
and Grandma Alice




"I worked on one of my poems all morning and I
took out a comma. In the afternoon I put it back in."

-- Oscar Wilde --

# 1) General Introduction

The application of scientific principles to sport and exercise dates back to at least the 5th century BC, with the prominent Greek physician Hippocrates (460 – 377 BC) receiving much of the credit for early ideas. While ancient Greek beliefs were based purely on empirical wisdom, excerpts translated from Hippocrates' Regimen by W. H. S. Jones and cited by Berryman (2003) demonstrate observational theories that were not so distant from our current scientific views:

> "Eating alone will not keep a man well; he must also take exercise. For food and exercise, while possessing opposite qualities, yet work together to produce health. For it is the nature of exercise to use up material, but of food and drink to make good deficiencies. And it is necessary, as it appears, to discern the power of the various exercises, both natural exercises and artificial, to know which of them tends to increase flesh and which to lessen it." (Hippocrates, translated by W. H. S. Jones, cited in Berryman, 2003, p.3)

While the evolutionary processes of studying and applying science to sport and exercise have spanned more than two thousand years, there have been rapid developments in recent times. This is demonstrated by the vast increase in sport- and exercise-related university courses now on offer (British Council, 2004; UCAS, 2010). The ultimate aim of sport science is to understand and enhance human sporting performance (Bishop, 2008). Exercise science, by contrast, has been defined as "the scientific study of human movement performed to maintain or improve physical fitness" (United States National Library of Medicine, 2003). While the distinction is subtle, the difference between sport and exercise sciences is in the respective foci on physical performance and physical fitness. This is exemplified in the objectives of both the English Institute of Sport, which has a specific aim "to make a performance impact at an international level" (English Institute of Sport, 2010) and the British Heart Foundation National Centre, which is committed to "developing and promoting initiatives that will help professionals stimulate more people to take more activity as part of everyday life" (British Heart Foundation National Centre, 2010). It is this differentiation between optimising athletic

performance and ensuring health and well-being that shapes the two separate strands of study.

As outlined by the British Association of Sport and Exercise Sciences (BASES), the scientific study of sport and exercise incorporates psychology, biomechanics and physiology (BASES, 2010). While the three disciplines interact dynamically in applied settings this thesis will focus on the latter, the study of how the body adapts physiologically to the acute stress of exercise, or physical activity, and the chronic stress of physical training (Wilmore *et al.*, 2008). Specifically, the physiological responses to endurance exercise will be considered, which has been defined by Maughan and Gleeson (2004) as exercise predominantly reliant upon aerobic energy metabolism. While endurance exercise can incorporate intermittent-type sports such as football, basketball and tennis, this thesis will focus on continuous-type activities and cycle ergometry, in particular.

The study of endurance exercise has evolved with the development of sport and exercise sciences and as such, so too has the associated terminology. Four inter-related concepts that will feature heavily throughout this thesis include 'aerobic endurance', 'aerobic fitness', 'aerobic capacity', and 'aerobic power', all of which have incurred a range of definitions in the scientific literature. For clarification, and to retain consistency throughout this thesis, definitions of these terms have been based on four key review papers (Bassett & Howley, 2000; Bosquet *et al.*, 2002; Coyle, 1999; Jones & Carter, 2000) and are described in table 1.1. Theoretical examples of how each would be tested and interpreted have been included in the table.

Table 1.1: Theoretical descriptions of four key aerobic-based terms with applied examples, where Athlete A attains a superior measure over Athlete B

| | | |
|---|---|---|
| **Aerobic Endurance** | Definition | The ability to sustain a high fractional utilisation of $\dot{V}O_{2max}$ during exercise over a set distance or period of time |
| | Test | Individual lactate threshold (LT) is measured and expressed as a percent of $\dot{V}O_{2max}$ |
| | Athlete A | In a 45-min time-trial a high relative $\dot{V}O_2$ may be sustained (e.g., 90 % of $\dot{V}O_{2max}$), due to a high relative LT |
| | Athlete B | In a 45-min time-trial a low relative $\dot{V}O_2$ is sustained (e.g., 75 % of $\dot{V}O_{2max}$), due to a low relative LT |
| **Aerobic Fitness** | Definition | The ability to deliver and utilise oxygen for energy provision during exercise |
| | Test | Assess absolute LT, $\dot{V}O_{2max}$, economy or efficiency and $\dot{V}O_2$ kinetics using incremental and constant-load tests |
| | Athlete A | LT = 220 W, $\dot{V}O_{2max}$ = 4.6 L·min$^{-1}$, economy = 9.5 mL·min$^{-1}$·W$^{-1}$ and $\dot{V}O_2$ fast component (time constant, $\tau$) = 13.1 s |
| | Athlete B | LT = 130 W, $\dot{V}O_{2max}$ = 3.1 L·min$^{-1}$, economy = 11.2 mL·min$^{-1}$·W$^{-1}$ and $\dot{V}O_2$ fast component (time constant, $\tau$) = 22.5 s |
| **Aerobic Capacity** | Definition | The amount of energy that is derived from aerobic metabolism during exercise over a set distance or period of time |
| | Test | The aerobic energy yield is quantified by measuring $\dot{V}O_2$ (1 L $O_2$ consumed ≈ 20 kJ energy) |
| | Athlete A | During 30 min of exhaustive exercise, aerobic energy yield = 1800 kJ |
| | Athlete B | During 30 min of exhaustive exercise, aerobic energy yield = 1200 kJ |
| **Aerobic Power** | Definition | The power output that can be sustained by aerobic metabolism during exercise over a set distance or period of time |
| | Test | The power output generated from aerobic energy sources is quantified by multiplying aerobic capacity by efficiency |
| | Athlete A | During the same 30 min of exercise as above, aerobic power output (assuming 20% efficiency) = [1800 kJ / 30 min] x 20% = 200 W |
| | Athlete B | During the same 30 min of exercise as above, aerobic power output (assuming 20% efficiency) = [1200 kJ / 30 min] x 20% = 133 W |

LT: lactate threshold

A priority of exercise physiologists working with endurance athletes is to enhance performance by off-setting fatigue, whereby fatigue may be regarded as a reduction in velocity or power output. As well as using external aids, such as nutritional and ergogenic supplements, this is achieved in a performance setting by maximising central and peripheral adaptations to physical training. For endurance athletes, performance is enhanced through increases in markers of aerobic fitness such as maximal oxygen uptake ($\dot{V}O_{2max}$), lactate threshold (LT) and efficiency (Joyner &

Coyle, 2008).   In non-performance settings (i.e., general populations exercising for health) similar adaptations are desirable due to the strong links between increased aerobic fitness and reduced risk of disease and lower mortality rates (Bouchard *et al.*, 2007; Hardman & Stensel, 2003).   However, a major problem associated with measuring aerobic fitness is that laboratory facilities and expertise are required for obtaining and interpreting the relevant data.   With elite athletes these types of measurements are sometimes possible, but among the general population the opportunity to receive regular physiological assessment is extremely rare.   As such, the practical limitations of monitoring improvements in aerobic fitness reduce the efficacy of applying physiological principles across a wide variety of sport and exercise settings.

Critical Power (CP) is a theoretical construct that has been proposed to reflect the highest exercise intensity that is solely dependent on a renewable aerobic energy supply (Scherrer & Monod, 1960).   According to table 1.1, therefore, CP may be considered synonymous with a 'maximal aerobic power'.   However, maximal aerobic power (MAP) is a term often used by exercise physiologists to describe $\dot{V}O_{2max}$, or the power output associated with $\dot{V}O_{2max}$ (Bernard *et al.*, 2009; Cooke *et al.*, 1997; Edwards *et al.*, 2003; Guiraud *et al.*, 2010; Jones & Doust, 1996; Le Chevalier *et al.*, 2000), and as such, interchange between the terms 'CP' and 'MAP' are avoided.   A thorough explanation of the CP construct is presented in chapter 2 but in brief, the parameter estimate is derived by modelling power output and time data from a series of short ($\sim 3 - 15$ min), exhaustive exercise trials.   The asymptote of the hyperbolic function between mechanical power output and time represents CP, which implies an exercise intensity that can be sustained for an infinite period of time (figure 1.1).   In terms of human function, the French authors acknowledged this limitation of the construct by describing exercise at CP to last only "un temps très prolongé" (Scherrer & Monod, 1960).   Given the ease of calculating CP in almost any performance or exercise setting, it may be considered preferable to alternative measures of aerobic fitness.
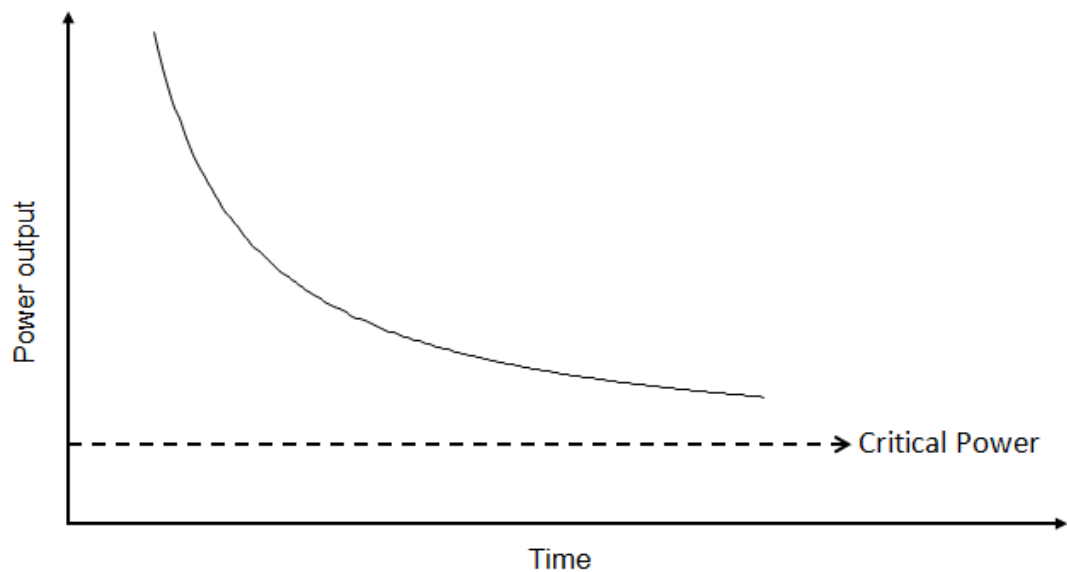
Figure 1.1: The hyperbolic relationship between power output and time to exhaustion, where the horizontal asymptote of the curve represents Critical Power

The limitations of the CP construct are multiple. Firstly, the CP estimate derived from the mathematical model is not valid for an exercising human, since exercise at CP is not sustainable for an infinite period of time. Secondly, given the requirement for anaerobic energy provision at the onset of exercise, exercise at CP is never fuelled solely by aerobic metabolism. Thirdly, since the parameter estimate for CP is modelled from exhaustive exercise trials, it is not reflective of a direct physiological response. Vandewalle *et al.* (1997) also point out that the modelling implicitly assumes that (i) performance is determined by metabolic factors (whereas the origin of fatigue could be electrolyte imbalances, central and nervous fatigue, etc.), and (ii) mechanical efficiency or energy cost are independent of power output or velocity, respectively, which is not the case for cycling or swimming. Despite these limitations, positive correlations have been reported between CP and many traditional markers of aerobic fitness (Housh *et al.*, 1991; Jenkins & Quigley, 1992; McLellan & Cheung, 1992; Moritani *et al.*, 1981; Pringle & Jones, 2002), as well as between CP and endurance performance that lasts longer than the durations used within the CP model (Greco & Denadai, 2005; Kolbe *et al.*, 1995; Smith & Jones, 2001). Furthermore, CP has been shown to increase following endurance but not strength training (Bishop & Jenkins, 1996; Jenkins & Quigley, 1992).

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While there is substantial evidence relating CP to other markers of aerobic fitness and endurance, the physiological responses to exercise at CP remain unclear (see chapter 3 for a full critique of the current literature). As such, the true physiological underpinnings of CP are not fully understood and the application of CP as an aerobic measure in practical settings, for a range of population groups, is limited. With this in mind, it is the purpose of this thesis to investigate the application of the CP construct to endurance exercise.

## 2) Review of the Relevant Literature: The Critical Power Construct

### 2.1) Modelling the work-time relationship

*2.1.1) The evolution of work-time models*

The historical development of modelling performance against time (where 'performance' may take the form of work, power output, distance or velocity) has seen early empirical models using world record data evolve into systems models based on human physiology. An outline of the key developments, until the introduction of the CP model in 1954, is illustrated in figure 2.1. Early observations of human endurance showed that distance covered while running is not linearly related to event duration (Kennelly, 1906) and that a smooth curve may be obtained when plotting running velocity against race distance (Meade, 1916). The most recent world record data for running events up to the marathon distance are illustrated in figure 2.2 and demonstrate this curvilinear relationship between average velocity and distance covered. It can be seen that average velocity approaches an asymptote as distance tends to infinity and this intensity was described vividly by Francis (1943) as "being for a "perfect runner" the "dog trot" velocity" (p. 315).

Closer inspection of the first three data points on figure 2.2 demonstrates a limit to human performance at the opposite end of the spectrum (i.e., a peak average velocity). It was suggested by Lietzke (1954) that peak average velocity is achieved over approximately 150 m. This is supported by the world best time of 14.35 s, set by Usain Bolt in a street race in Manchester in May 2009 (Kessel, 2009b). This world best 150-m time reflects an average velocity of 10.45 $m \cdot s^{-1}$, which is faster than the average velocity for either the 100-m (10.44 $m \cdot s^{-1}$) or the 200-m (10.42 $m \cdot s^{-1}$) world records set by Usain Bolt in Berlin in August 2009 (Kessel, 2009a). It is hypothesised that the acceleration phase of a 100-m race is more detrimental than the fatigue effect experienced over the longer 150-m race; by contrast, the fatigue effect experienced over a 200-m race appears to outweigh the slowing effect of the acceleration phase of the shorter 150-m race.

Kennelly analysed world records to develop a logarithmic distance-time relationship for running

Hill showed that the highest velocity sustainable over a fixed time is determined by the individual's maximum rate of oxygen uptake and maximum oxygen debt that can be tolerated

Francis developed a hyperbolic function between velocity and the log of distance using world records for 400 m to 19 km. The asymptote of the hyperbola represented a sustainable "dog trot" velocity of 3.2 m·s⁻¹ for a "perfect" runner

Lietzke noticed two changes in the slope of the distance-time relationship at around 1 km and 20 km and also noted that maximal velocity (35.9 km·h-¹) is achieved at 15 s, so the velocity-time curve should not include distances < 150 m

$$\ln t = 8/9 \cdot \ln d - 1.2307$$
(t = time; d = distance)

$$\log t = a \cdot \log P + b, \ a < 0$$
(t = time; P = power; a and b are constants)

$$\log d = k \log t + \log a$$

$$w = a + b \cdot t$$
(t = exercise duration; w = total work)

1906    1916    1927    1936    1943    1954

$$(\log d - 1.5) \cdot (v - 3.2) = 6.081$$
(d = distance; v = velocity)

Meade suggested that the position of world record data points around the relationship between velocity and distance could be used to identify physiological characteristics and potential

$$dy/dt = a_1 e^{-k_1 t} + a_2 e^{-k_2 t} + a_3 e^{-k_3 t} + a_4 e^{-k_4 t} + a_5 e^{-k_5 t}$$
(t = time; $a_n$ and k are constants)

Scherrer *et al.* introduced critical power (b) and work capacity (a) for local muscular work, based on a linear relationship between work and time

Große-Lordemann and Müller resumed Kennelly's work and derived mathematical relationships for cycle ergometer exercise using power-time curves

Henry proposed that the changes from alactic to lactic anaerobic metabolism, then fuel sources for aerobic metabolism from glycogen to fat, were related to the duration of exercise and hence characterised the velocity-time relationship

Figure 2.1: Significant developments in the work-time modelling of human endurance

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Figure 2.2: The velocity-distance relationship for male world-record data for 100-m to marathon-distance running events and the world best 150-m time (up-to-date in September 2010)

*2.1.2) Introduction to the Critical Power construct*

The CP construct originates from work by Scherrer *et al.* (1954), who identified the following linear relationship between dynamic local muscular work (w) and the tolerable duration for continuing this work (t):

$$w = a + b \cdot t \qquad\qquad \textit{equation 1}$$

The constants a and b are derived from a series of exhaustive exercise trials performed at various high-intensity power outputs (figure 2.3). Scherrer and Monod (1960) defined factor b as CP within this equation, which mathematically equates to a power output that can be sustained for an infinite period of time. However, the authors defined CP more realistically: "Lorsque la puissance de travail supposée est… égale à celle du facteur *b*, le travail peut être poursuivi pendant un temps très prolongé" (p. 426), which translates to: "When the power output is… equal to factor *b*, the work may be continued for a prolonged period of time".

The work of Scherrer *et al.* (1954) and Scherrer and Monod (1960) was extended by Monod and Scherrer (1965) and the latter publication, written in English rather than French, is typically cited as the original study of CP. By substituting w with the product of power output (P) and t (i.e., w = P · t), the authors rearranged *equation 1* to give a hyperbolic expression of the same mathematical concept:

$$t = a / (P - b) \qquad\qquad \textit{equation 2}$$

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The constants a and b are again derived from exhaustive trials but rather than reflecting the y-intercept and the slope (as in *equation 1*), a and b denote the curvature constant and vertical asymptote of the function, respectively (figure 2.4).
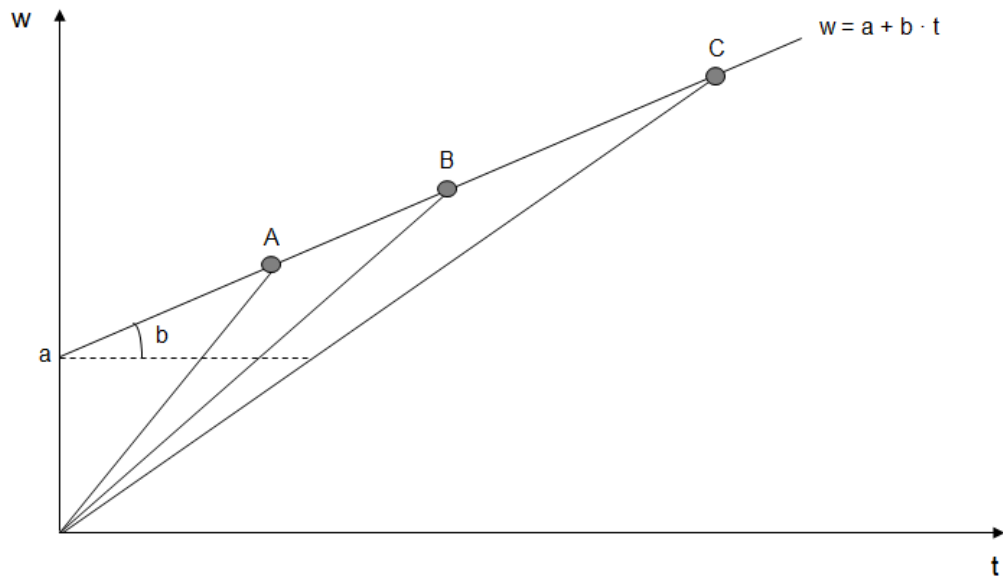


Figure 2.3: An example of the linear relationship between exhaustive work (w) and tolerable duration (t) using three exhaustive exercise trials (A, B and C) where the y-intercept (a) represents the anaerobic work capacity and the slope (b) represents Critical Power (adapted from Monod and Scherrer, 1965)
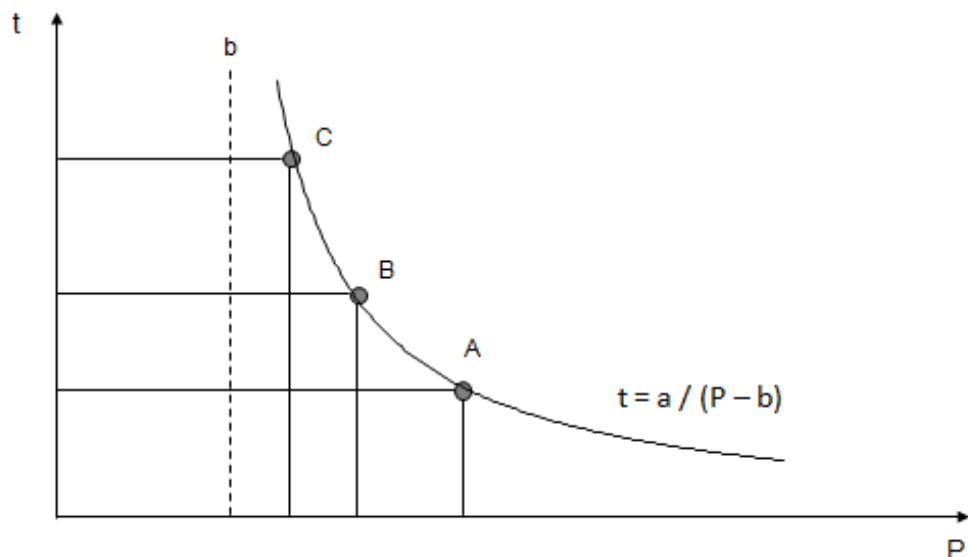


Figure 2.4: An example of the hyperbolic relationship between tolerable duration (t) and power output (P) using three exhaustive exercise trials (A, B and C) where the curvature constant (a) represents the anaerobic work capacity and the vertical asymptote of the curve (b) represents Critical Power

When muscular work was performed to exhaustion under occlusion (i.e., in the absence of oxygen), Monod and Scherrer (1965) reported that the w-t slope *(equation 1)* was equal to zero and w was constant, regardless of t. They therefore concluded that the w-t slope, representing CP, reflects the upper limit of P that is solely dependant on a renewable aerobic energy supply. The maximum fixed work capacity sustainable by anaerobic energy was assumed to be represented by the y-intercept, a, which was thus defined as the anaerobic work capacity (AWC). Two major limitations arise from this two-parameter systems model, which are perhaps more clearly understood with reference to figure 2.4, and these are: (i) that CP reflects a work rate that would be infinitely sustainable (i.e., as $P \rightarrow CP$, $t \rightarrow \infty$), and (ii) that some infinite power output can be maintained as long as time > 0 (i.e., as $t \rightarrow 0$, $P \rightarrow \infty$). In reality, of course, no constant-load exercise can be maintained for an infinite period of time as fatigue will eventually ensue (due to substrate depletion, dehydration, hyperthermia or sleep deprivation, for example). As such, CP was defined to correspond to the maximum rate that a given muscle can sustain "for a very long time without fatigue" (Monod & Scherrer, 1965) and it has since been recognised that a peak maximal power output prevents P approaching infinity as t approaches zero (Morton, 1996).

*2.1.3) Developments to the Critical Power construct*

The aforementioned relationships *(equations 1* and *2)* were originally developed for synergic muscle groups only (e.g., the quadriceps femoris, biceps brachii and triceps brachii) and it was not until much later that the CP model was extended to whole body exercise in the laboratory using cycle ergometry (Moritani *et al.*, 1981). Moritani *et al.* (1981) modified the two-parameter model by solving *equation 2* for P, hence transforming the hyperbolic function into a linear relationship between P and the inverse of t ($t^{-1}$):

$$P = a \cdot t^{-1} + b \qquad\qquad \textit{equation 3}$$

In this equation the gradient of the slope (a) reflects the AWC and the y-intercept (b) represents CP. Although it has been noted that the hyperbolic function given by *equation 2* more correctly defines the CP model in mathematical terms, since t is the dependent variable and P is the independent variable in exhaustive cycle ergometry

(Morton & Hodgson, 1996), the linear expression given by *equation 3* provides comparable CP estimates (see section 2.1.4) and excellent fits to real-world data. Therefore, since *equation 3* allows estimates for CP and AWC to be obtained more simply, it would seem favourable for use in applied settings.

Due to the real-world limitations of the aforementioned 2-parameter models (i.e., that no exercise can continue *ad infinitum* and that power output does not become infinitely large as t approaches zero), alternative models have been introduced to better reflect human performance and physiological systems. Hopkins *et al.* (1989) developed an exponential model that included a third parameter, $P_{max}$, that would occur at t = 0 (i.e., an instantaneous maximal power output fuelled by energy stored in the muscle) and a corrective time constant, $\tau$, to account for the delay in aerobic power development:

$$P = CP + (P_{max} - CP) \cdot (e^{-t/\tau})$$ *equation 4*

Another method to overcome the problem of an infinite P existing as t → 0 was proposed, without reference to *equation 4*, by Morton (1996):

$$t = AWC / (P - CP) + AWC / (P - P_{max})$$ *equation 5*

Additional extensions to the original 2-parameter models have been proposed to account for physiological occurrences such as fatigue and energy supply (Péronnet & Thibault, 1989), but due to the modelling complexities and numerous assumptions these have not been popular in applied research and as such, will not be discussed further within this thesis.

*2.1.4) Effects of model choice on Critical Power and Anaerobic Work Capacity estimates*

The characteristics and applications of the five models described by *equations 1 – 5* are summarised in table 2.1. An analysis of the CP and AWC estimates obtained from these models reveals that the choice of model may have a significant impact on each parameter estimate.

Table 2.1: Characteristics of the five Critical Power models

| Equation | Model | Type | Duration | Advantages | Disadvantages |
|---|---|---|---|---|---|
| 1 | $w = AWC + CP \cdot t$ | Linear 2-parameter | 3 – 20 min | Easy to generate the data points required for modelling. Straightforward to derive the parameters from the linear model. | The dependent variable, w, is calculated using t, the independent variable ($w = P \cdot t$), so any error in t will be reflected in w. Over-simplifies the physiology of human performance, limiting predictive ability for short- and long-duration exercise. |
| 2 | $t = AWC / (P - CP)$ | Non-linear 2-parameter | 3 – 20 min | Easy to generate the data points required for modelling. t and P are correctly identified as the dependent and independent variables, respectively. | Difficult for applied practitioners to derive parameters from the non-linear model. Over-simplifies the physiology of human performance, limiting predictive ability for short- and long-duration exercise. |
| 3 | $P = AWC / t + CP$ | Linear 2-parameter | 3 – 20 min | Easy to generate the data points required for modelling. Straightforward to derive the parameters from the linear model. | The independent and dependent variables are incorrectly positioned. Over-simplifies the physiology of human performance, limiting predictive ability for short- and long-duration exercise. |
| 4 | $P = CP + (P_{max} - CP) \cdot (e^{-t/\tau})$ | Exponential | < 3 min | Requires only short exhaustive trials to generate data points for modelling. Accounts for an upper limit to power production and the delayed aerobic response at the onset of exercise. | Is restricted to predicting exercise performance lasting up to only 1 min. Does not provide an estimate of AWC. |
| 5 | $t = AWC / (P - CP) - AWC / (P + P_{max})$ | 3-parameter | 1 – 20 min | Accounts for an upper limit to power production. | Difficult for applied practitioners to derive parameters from the non-linear model. An additional "very high intensity" trial is required and $P_{max}$ is highly variable. |

'Duration' refers to the time period over which data points are obtained for modelling

A number of studies have shown that the non-linear P-t model produces the smallest estimate of CP, followed by the linear w-t model, and that the linear P-t$^{-1}$ model produces the highest values for CP (Bull *et al.*, 2000; Gaesser *et al.*, 1995; Hill *et al.*, 2003; Housh *et al.*, 2001). The reverse effect has been shown for AWC, whereby the largest AWC estimate is derived from the P-t model and the smallest AWC estimate is derived from the P-t$^{-1}$ model (Gaesser *et al.*, 1995; Hill *et al.*, 2003). These relationships between model choice and the size of resultant CP and AWC estimates are illustrated in figure 2.5, using an example data set. Despite the differences in CP and AWC estimates, experimental data would be considered to provide good prediction equations for all three of the 2-parameter models in the four cited studies, with r > 0.91 (Vincent, 2005). Furthermore, differences in mean CP estimates between models were small, increasing by factors of only 0.01 to 0.10 from the smallest to the largest estimate within each of the studies. Conversely, the variation in AWC reported by Hill *et al.* (2003) was large, with the mean value for the P-t model 2.43 times greater than the P-t$^{-1}$ model (90 versus 37 m). It is likely due to the inherent sensitivity of the AWC parameter to small changes in t that magnifies any differences in its estimation.

The exponential model *(equation 4)*, which was originally developed as an anaerobic test using performance trials lasting only 10 s to 3 min, elicits greater CP estimates compared with the 2-parameter models (Bull *et al.*, 2000; Bull *et al.*, 2008; Gaesser *et al.*, 1995; Hill *et al.*, 2003; Housh *et al.*, 2001). When predictive trials used within the exponential model are longer than 3 min, the CP estimate can actually exceed the exercise intensity of a predictive trial. This clearly indicates a different physiological basis for CP when compared with the estimates derived from the 2-parameter models. By contrast, the 3-parameter model described by *equation 5*, which was also intended to enhance the physiological meaning of CP by including P$_{max}$, results in a lower estimate of CP and a higher estimate of AWC (Bull *et al.*, 2000; Bull *et al.*, 2001; Bull *et al.*, 2008; Chatagnon *et al.*, 2005; Gaesser *et al.*, 1995; Hill, 2004; Hill *et al.*, 2003; Housh *et al.*, 2001; Morton, 1996). These findings led to the notion that 2-parameter models "over-estimate" CP (Morton, 1996).
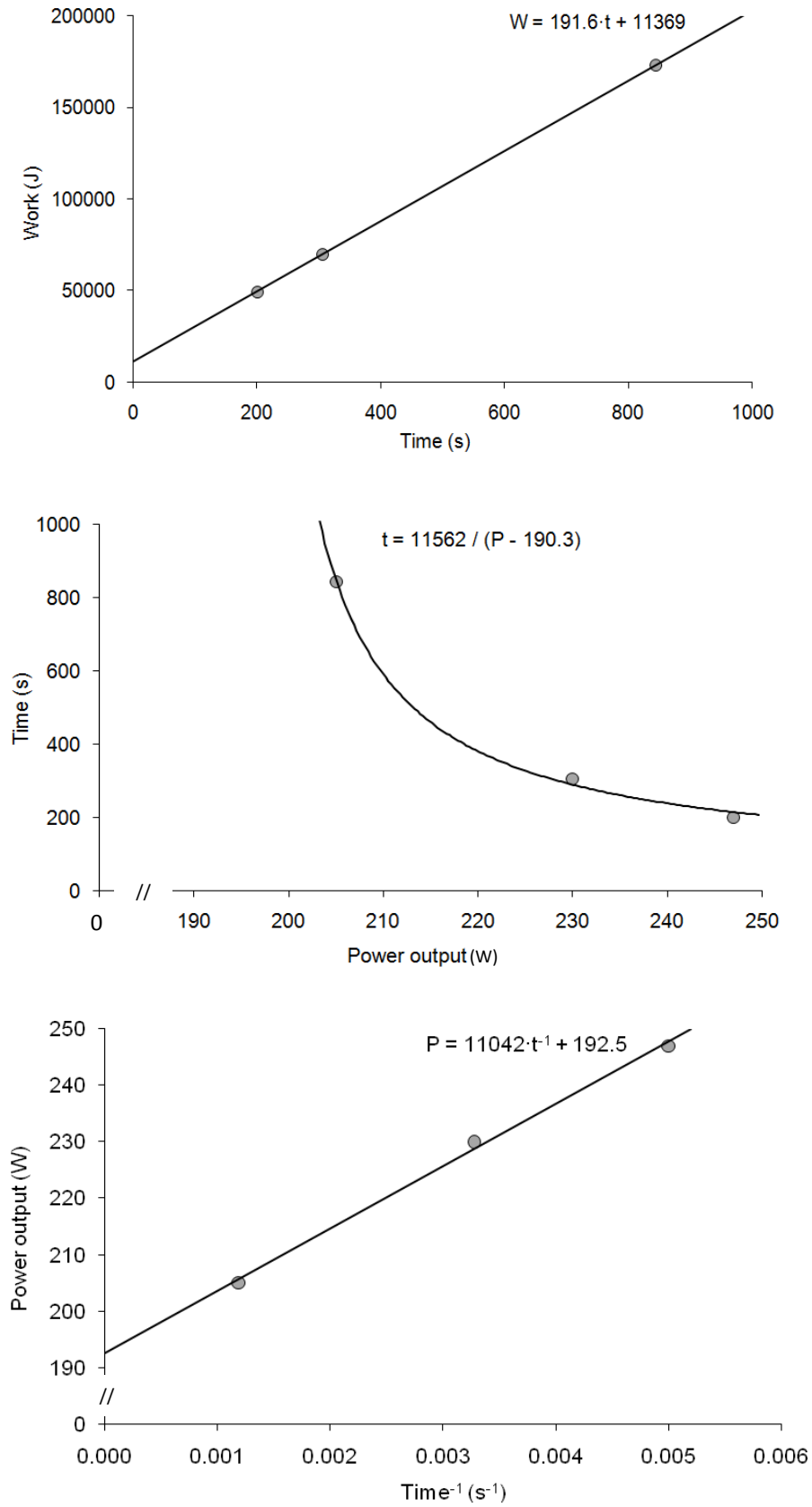
Figure 2.5: Example Critical Power estimates derived from the same data set using the three 2-parameter models described by *equations 1*, *2* and *3*, respectively

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Despite the attempts to improve CP estimates, the exponential and 3-parameter models involve more complex modelling procedures. Moreover, the exponential model introduced by Hopkins *et al.* (1989) is not valid for exercise durations > 3 min. It is accepted that the 3-parameter model is advantageous in that it overcomes the assumption of infinite power when time approaches zero, and that the fit of the model tends to be superior to the 2-parameter models, but it has been demonstrated that CP estimates cannot be derived from the 3-parameter model in some cases where the shortest exercise trials are > 4 min in duration (Jenkins *et al.*, 1998). As such, 2-parameter models have been suggested as more valid in estimating the capacity for sustained aerobic power (Chatagnon *et al.*, 2005) and since practical application is of interest in this thesis, only the 2-parameter models will be discussed further.

*2.1.5) Variability of the Critical Power and Anaerobic Work Capacity parameter estimates*

By repeating the CP modelling process one week after an initial set of tests, test-retest variability for CP and AWC estimates has been calculated as $r^2 = 0.92$ and 0.62, respectively (Gaesser & Wilson, 1988). In their study, Gaesser and Wilson (1988) showed that the CP value increased for nine out of the 11 participants (the non-significant mean increase was 3.4 %) and the mean ± SD magnitude of the absolute change from the first estimate to the second was 4.1 ± 3.7 %. The AWC score increased for only seven out of 11 participants and decreased for the other four, with the mean ± SD absolute change calculated as 10.3 ± 7.7 %. Although no significant differences were observed for test-retest estimates of CP or AWC for the grouped data, these results indicate that AWC appears to be more variable than CP.

Smith and Hill (1993) support the notion that CP is less variable than AWC, with test-retest correlation coefficients for CP of $r = 0.92$ and 0.90 for males and females, respectively, and for AWC of $r = 0.80$ and 0.64 for males and females, respectively. While there was no test-retest change in the AWC estimate (18.3 to 18.0 kJ for males and 10.6 to 10.8 kJ for females), CP increased significantly (by 5 − 6 %). This is similar to the tendency outlined by Gaesser and Wilson (1988) for CP to increase from test to retest and suggests that learning effects may be associated with

calculating CP. As such, it would seem appropriate to include familiarisation sessions in any protocol prior to recording experimental data for CP measurement.

Bishop and Jenkins (1995) used one familiarisation session and demonstrated a significant increase (3.4 %) from the familiarisation to the first experimental estimate of CP, whereas first to second experimental estimates of CP were not different. The test-retest correlations were high (r = 0.99), unlike those for the AWC estimates (0.64 ≤ r ≤ 0.88). Given the high variability of AWC that has been characteristic of most test-retest data, the anaerobic-based parameter estimate derived from the w-t and P-t relationships does not appear reliable or, therefore, valid. As such, this review of literature and the thesis will be delimited to the CP parameter.

## 2.2) Methodological issues

The CP parameter has been estimated using a variety of different protocols that have varied the number of trials used, the recovery durations between trials and the ranges of t and P. This section aims to outline the most appropriate CP-determination protocol in order to present a consistent method that may be routinely followed by researchers in the future.

### 2.2.1) Number of trials and recovery between trials

Experimental studies using cycle ergometry to determine CP have used only two trials (Housh *et al.*, 1991), as many as seven trials (Gaesser *et al.*, 1995), or more commonly, some number in between. The need for only two trials is an attractive prospect for applied sport scientists, practitioners or coaches who may deal with large participant populations or smaller groups of high-level athletes. In support of using fewer trials, scientific evidence exists to show that CP may be accurately determined from only two data points (Housh *et al.*, 1990). The authors recommended using two workloads that induce exhaustion within 1 − 10 min, whereby the two durations must differ by at least 5 min. Despite the data presented by Housh *et al.* (1990), it must be acknowledged that when only two data points are used then the risk of obtaining an inaccurate estimate of CP is inevitably high. Any error that exists in either of the

trials, due to fatigue or a lack of motivation, for example, would greatly affect the model estimate.

While it is true that more trials reduce the impact of one or more erroneous data points, it is worth questioning the need for as many as seven trials, particularly since "the attractiveness of the critical power concept diminishes if too many predicting trials are required for generation of parameter estimates with a reasonable degree of accuracy" (Hill, 1993, p.238). Poole (1986) recommended using at least four to five exhaustive trials to ensure that the potential risk of over-estimating CP due to measurement error was not an issue[1]. However, it seems that this would not be necessary if power output could be measured directly at the crank, as is possible with SRM (Schoberer Rad Messtechnik) cycle ergometers, since the problem of over-estimating data points would not arise. Data presented by Housh *et al.* (1990) indicate that two and three trials are as effective in producing CP estimates as four trials (using *equation 1*), irrespective of whether familiarisation trials are provided or not. Therefore, perhaps the most balanced recommendation would be to use three trials. Using three trials to determine CP is attractive to the experimenter, preserves confidence in accuracy and has been the preferred choice in a number of studies that have used cycle ergometry (Bishop & Jenkins, 1995;1996; Brickley *et al.*, 2002; Carter *et al.*, 2005; Coats *et al.*, 2003; Green *et al.*, 1994; Jenkins & Quigley, 1991;1992;1993; Puente-Maestu *et al.*, 2003).

With regard to recovery between trials, CP determination tests have been completed over one day or over a series of days. Bishop and Jenkins (1995) compared the two methods by prescribing three CP determination trials on either one day or over three consecutive days. They found no significant differences between the mean CP values calculated under each set of conditions and concluded that, for this population group (untrained females), a 3- or 24-h recovery duration between tests elicits similar CP estimates when using the w-t model. This has practical implications for use of the CP model in a variety of environments. However, further investigation into the shortest

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[1] Poole (1986) has suggested that generating the necessary force on a cycle ergometer when very high work rates are required can be difficult. Therefore, any deficit in accumulated work that is unaccounted for during tests implemented at high power outputs would lead to CP data points being over-estimated (since less work would have been achieved than was thought to have been achieved).

recovery time that could generate valid CP estimates would be useful, as well as investigations using different population groups.

*2.2.2) Effect of trial duration and intensity*

It was explained in section 2.1.4 that the exponential model was originally developed to explain power-time relationships for exercise lasting < 3 min and the 3-parameter model *(equation 5)* also requires at least one very short-duration, high-intensity predictive trial in order to obtain a reasonable estimate for $P_{max}$. It would seem, therefore, that the duration of predictive exercise trials are somewhat dependent on the model being used and must lie within the range of times for which the relationship was developed. Consistent with the specification that trials must lie within the range of times defined by the relationship, Hill (2004) suggested that traditional CP modelling using the 2-parameter model ought to avoid very short tests (i.e., less than 2 – 3 min), so that the effects of aerobic inertia are minimised, as well as very long tests (i.e., greater than 15 – 20 min), in order to avert the confounding effects of dehydration, boredom and muscle glycogen depletion. The use of only short-duration tests compared with a range of shorter and longer tests has been demonstrated by Vautier *et al.* (1995). The CP estimates derived from only short exhaustive trials at 100 and 120 % of MAP were compared with those derived from a range of short (3.5 min) to long (35 min) exhaustive trials (at 60, 73, 86, 100 and 120 % of MAP). The CP estimate derived from the two short trials was significantly higher than that derived from all five trials (80 ± 6 versus 69 ± 6 % of MAP, respectively).

Similarly, two further studies have compared CP estimates derived from short-, long- and all-duration trials (Bishop *et al.*, 1998; Jenkins *et al.*, 1998). Jenkins *et al.* (1998) prescribed five trials at various power outputs, which led to exhaustion within 4.2 – 25.7 min, then modelled CP in three ways using the w-t model (all fits were excellent with $0.995 \leq r \leq 0.999$). The three lowest-intensity w-t data points (of longest duration) led to the smallest CP estimate (268 W), while the three highest-intensity w-t data points (of shortest duration) led to the largest CP estimate (321 W). The CP estimate obtained from all five data points was between the two (285 W). Consistent with these results, Bishop *et al.* (1998) revealed that w-t and P-t models elicited significantly lower average CP estimates (164 W) when trial durations were longest

(193 – 485 s), and significantly higher average CP estimates (201 W) when trial durations were shortest (68 – 193 s). Data points spanning the whole range of durations (69 – 485 s) generated a CP estimate between the two (176 W). It was suggested that CP determination trials for 2-parameter modelling should last > 3 min to maximise the anaerobic energy yield and ensure aerobic metabolism has reached a steady state, and < 20 min so as not to be significantly influenced by factors such as diet, hydration, temperature regulation or motivation (Bishop *et al.*, 1998).

With an upper limit of 15 min having been previously used for time to exhaustion (TTE) trials (Hill, 2004), the best practice may be to standardise CP-determination trial durations to within 3 – 15 min. This may be achieved by imposing exercise intensities as a proportion of MAP or $\dot{V}O_{2max}$. As a reference, previous studies have used work rates of 65 – 135 % of MAP (or an equivalent measure of peak aerobic power attained during an incremental ramp test to fatigue) and 90 – 110 % of $\dot{V}O_{2max}$ to elicit exhaustion within 2 – 15 min (Carter *et al.*, 2005; Dekerle *et al.*, 2003; Hill *et al.*, 2002; Overend *et al.*, 1992).

*2.2.3) Reproducibility of time to exhaustion*

It was identified in section 2.1.5 that CP increases from a first to a second estimate by approximately 1 – 6 %, but that strong test-retest correlations exist (r > 0.92) and following a familiarisation trial, CP estimates do not differ (Bishop & Jenkins, 1995; Gaesser & Wilson, 1988; Nebelsick-Gullett *et al.*, 1988; Smith & Hill, 1993). These findings may be attributable to variations in the TTE tests that are used in determining CP. That is, if TTE values increase from a first to a second trial over a series of tests at fixed power outputs then the CP estimate, which is derived from the TTE data, would also change.

McLellan *et al.* (1995) showed mean TTE to increase over five cycling trials at 80 % of $\dot{V}O_{2max}$ from 14.4 to 18.2 min, implying that a learning effect may be associated with repeated TTE trials. However, this difference was not statistically significant, probably due to the large inter-individual variability of TTE from trial to trial, whereby coefficient of variation (CV) values of up to 31.4 % were reported. Bishop

and Jenkins (1995) investigated the reliability of different duration TTE tests for CP modelling and showed that TTE during short- and medium-duration tests (i.e., $\sim 1 - 5$ min) did not change significantly from a first to a third trial but that the TTE during long-duration tests (i.e., $\sim 8 - 16$ min) increased significantly from trials 1 to 2, and again from trials 2 to 3. Similarly, Smith and Hill (1993) showed a greater improvement in longer TTE tests compared with shorter tests over repeated trials. These data provide evidence to suggest that TTE tests for CP modelling become less reliable as duration increases. As such, the recommendation to limit the longest CP-determination trials to 15 rather than 20 min is further supported.

Hinckson and Hopkins (2005) have demonstrated excellent reliability of TTE tests compared with other tests of endurance performance by showing test-retest error of measurement estimates of < 3 % during constant-load running exercise (lasting $1 - 10$ min). The authors acknowledge that TTE tests have been shown to produce large test-retest variability, but suggest that this is an artefact of the P-t relationship, whereby small random changes in power lead to larger random changes in TTE. Despite this modelling effect, large errors in TTE have been suggested by Vandewalle *et al.* (1997) to have a small effect on subsequent estimates of CP.

*2.2.4) Effect of cadence*

Different cycling pedal rates, or cadences, have been widely investigated in the literature and varying relationships between mechanical and physiological responses to increased cadence depending on the measured variable have been revealed. For example, post-exercise blood lactate concentration ($[La^-]_{bl}$) appears to increase progressively with increases in cadence from 35 to 115 rev·min$^{-1}$ following sub-maximal, constant-load exercise (Brisswalter *et al.*, 2000; Pringle *et al.*, 2003; Whitty *et al.*, 2009). In addition, a decrease in gross efficiency (i.e., the ratio of work done per min to energy expended per min) occurs with increasing cadence from 50 to 110 rev·min$^{-1}$ (Whitty *et al.*, 2009). By contrast, oxygen uptake ($\dot{V}O_2$), heart rate (HR) and integrated electromyogram (iEMG) slope responses have elicited parabolic-type relationships with increases in cadence, whereby intermediate cadences appear to minimise the physiological stress. For example, the $\dot{V}O_2$ and HR responses to a

fixed, sub-maximal workload were shown to be higher at 60 versus 80 rev·min$^{-1}$, but lower at 95 versus 110 rev·min$^{-1}$ (Brisswalter *et al.*, 2000). This pattern is supported by earlier work of Takaishi *et al.* (1996), who showed cycling at 70 rev·min$^{-1}$ to elicit a lower mean $\dot{V}O_2$ response compared with cycling at 50, 60, 80, 90 and 100 rev·min$^{-1}$. Takaishi *et al.* (1996) also reported neuromuscular fatigue, reflected by iEMG slope, and showed significantly slower fatigue responses at 80 and 90 rev·min$^{-1}$ compared with 50, 60, 70 and 100 rev·min$^{-1}$. These findings are associated with decreases in TTE at very low (50 rev·min$^{-1}$) and very high (108 rev·min$^{-1}$) cadences compared with intermediate (80 and 94 rev·min$^{-1}$) cadences (Nesi *et al.*, 2004; Nickleberry & Brooks, 1996).

These data suggest that gross efficiency is optimised at lower cadences but that cycling at intermediate cadences may delay the onset of cardiovascular and neuromuscular fatigue, thereby improving endurance performance. It is proposed that at high cadences (i.e., $\geq$ 100 rev·min$^{-1}$) there is a higher aerobic demand due to an increase in the internal work required to rotate the lower limbs more quickly. In addition, greater leg speeds have been associated with co-contraction and an increase in negative muscle work, due to activation dynamics and the need to control external movement (Neptune & Herzog, 1999). Takaishi *et al.* (1996) also relate earlier fatigue at higher pedal rates to changes in muscle fibre and motor unit recruitment. A greater contribution from fast-twitch type II muscle fibres has been proposed at higher cadences, which, compared with slow-twitch type I muscle fibres, would result in faster rates of muscle fatigue and more $O_2$ being consumed for the same amount of energy produced. This latter response is supported by data showing an increased amplitude of the $\dot{V}O_2$ slow component ($\dot{V}O_2$-SC) observed during constant-load exercise at higher (i.e., 108 – 115 rev·min$^{-1}$) compared with lower (i.e., 35 – 94 rev·min$^{-1}$) cadences (Nesi *et al.*, 2004; Pringle *et al.*, 2003).

The increased metabolic cost of performing exercise at higher pedalling frequencies has led authors to hypothesise that CP would be lower when cycling at high versus low cadences during the exhaustive trials (Carnevale & Gaesser, 1991). This theory has been supported by findings that CP estimates from each of the 2-parameter

models are significantly lower when exhaustive trials were cycled at 100 compared with 60 rev·min$^{-1}$ (Carnevale & Gaesser, 1991; Hill *et al.*, 1995). However, Barker *et al.* (2006) hypothesised that, despite a lower absolute CP estimate at higher pedalling frequencies, $\dot{V}O_2$ would be similar during exercise at CP when pedalling at 60 and 100 rev·min$^{-1}$ due to the parameter estimate representing a unique metabolic rate. This hypothesis was supported in that a lower CP was elicited when exhaustive trials were performed at the higher versus the lower cadence (189 ± 50 versus 207 ± 53 W at 100 and 60 rev·min$^{-1}$, respectively), yet $\dot{V}O_2$ after two minutes of exercise at the pedal-rate specific CP was similar for both pedalling frequencies (2.58 ± 0.53 versus 2.53 ± 0.60 L·min$^{-1}$ at 100 and 60 rev·min$^{-1}$, respectively). The authors concluded that the $\dot{V}O_2$ at CP may be considered a parameter of aerobic function, since it reflects a unique metabolic rate that is similar during exercise at different power outputs (i.e., the pedal-rate-specific CP) that is performed at different pedalling frequencies (Barker *et al.*, 2006).

In addition to the effects of cycling at either a high or a low cadence, the extent to which cadence drops off towards the end of an exhaustive trial does not appear to affect the CP estimate for tests performed on cycle ergometers that can control power output independent of cadence (Green *et al.*, 1995). The authors measured TTE during trials completed at 80 – 90 rev·min$^{-1}$ and encouraged participants to continue cycling until cadence dropped to 50 rev·min$^{-1}$. As long as the end-point cadence was consistent across trials, CP estimates were similar when TTE trials were terminated at 70, 60 or 50 rev·min$^{-1}$. In spite of these findings it is probably wise to limit the reduction in cadence below the rate maintained throughout the test, in order to minimise the effect of any delay in the response of the cycle ergometer to adjust resistance and maintain power output as cadence drops.

Imposing a set cadence appears to be necessary in controlling for the potential effects of cycling at various pedalling frequencies on TTE and CP estimates. However, optimal cadence, in terms of minimising neuromuscular fatigue and maximising energetic efficiency, appears to differ among individuals and may depend upon cycling experience and fitness level (Takaishi *et al.*, 1996). A number of studies have

investigated the effects of allowing individuals to pedal at a preferred rate, or a self-selected cadence (SSC). Takaishi *et al.* (1994) have shown that SSC reflects the pedalling rate at which neuromuscular fatigue is minimised for non-cyclists and SSC for trained triathletes is reportedly close to the neuromuscular optimum early on in sub-maximal exercise (Vercruyssen *et al.*, 2001). It is worth noting that optimal cadence may vary with test duration, as well as at various time-points within a test (Brisswalter *et al.*, 2000). However, these factors are difficult to overcome when test duration is unknown and when a constant cadence is required throughout a single test. As such, with additional findings showing TTE and MAP values to be higher at SSC compared with SCC ± 10 and 15 % (Nesi *et al.*, 2004; Weissland *et al.*, 1997), a fixed SSC within and between trials should provide a controlled, comfortable and near-optimal pedalling rate for a range of individuals.

*2.2.5) Practical recommendations*

This section of the literature review has provided a detailed analysis of the effects of modelling methods on estimates of the CP parameter. Given the range of models and methods used in the literature, the physiological responses to exercise at CP would be expected to differ significantly between studies. With a consistent method for determining CP, supported by comprehensive scientific reasoning, the application of CP as an exercise parameter may be investigated and compared between studies.

In section 2.1 it was reasoned that the exponential and 3-parameter models are complex and limited in their application and as such, 2-parameter models would remain the focus of the literature review. In addition, the linear 2-parameter models were shown to elicit good fits to the data and provide simpler methods for obtaining CP estimates compared with the non-linear model. Since the work component of the w-t model is a function of power output and time, so magnifies any error in either P or t, the P-t$^{-1}$ model (*equation 3*) is recommended here as favourable for obtaining CP estimates.

In section 2.2 the use of three exhaustive trials that span 3 − 15 min was justified. It was suggested that trials lasting < 3 min should be avoided in order to minimise the

effects of aerobic inertia, and the longer trials should be limited to 15 min to improve the reliability of the TTE data. While performing three trials on one day appears to produce similar CP estimates as performing trials over three consecutive days, only one study has investigated this effect so the ability to generalise results to wider populations is limited. As such, until further studies are carried out to investigate the impact of recovery duration for a range of individuals, the recommendation is to conduct controlled TTE trials on separate days.

In summary, in order to produce comparable literature regarding the physiology and application of CP, it is suggested that CP is modelled using:

- the linear P-$t^{-1}$ relationship: $P = AWC \cdot t^{-1} + CP$
- three TTE trials
- TTE trials that span 3 – 15 min
- TTE trials that have been performed on separate days
- a series of TTE familiarisation trials prior to data collection
- a cycle ergometer that controls power output independently of cadence
- a fixed cadence that is self-selected by the participant
- an end-point cadence that is close to the SSC

These criteria will be applied throughout all experimental studies within this thesis.

## 3) Review of the Relevant Literature: The Physiology of Critical Power

The previous chapter discussed the history and development of the CP construct and provided detailed information regarding the modelling issues and processes involved in obtaining a valid and reliable estimate of CP. It was suggested that CP reflects the highest power output that is dependent only on a renewable aerobic energy supply, but no further physiological basis for the construct was proposed. The aim of the current chapter, therefore, is to examine the physiology associated with CP and to discuss how CP relates to other markers of aerobic fitness.

Aerobic endurance was described in chapter 1 as the ability to sustain a high fractional utilisation of $\dot{V}O_{2max}$ and Coyle (1999) proposes that $\dot{V}O_{2max}$ and LT (i.e., markers of aerobic fitness) are fundamental factors that contribute to endurance performance. Given the positive correlations highlighted in chapter 1 between CP and traditional markers of aerobic fitness and endurance performance, it is possible that CP may also be considered a fundamental parameter that reflects aerobic fitness and contributes to endurance performance. To illustrate the physiological underpinning of CP according to the construct described in chapter 2, the theoretical $[La^-_{bl}]$ responses to exercise at CP and a range of other traditional aerobic markers have been presented in figure 3.1.

Consistent with the definition proposed by Smith and Jones (2001) for LT, which describes a sudden and sustained increase in the gradient of the work rate-$[La^-]_{bl}$ curve, the model demonstrates that, when exercising at the power output associated with LT (P-LT), $[La^-]_{bl}$ does not deviate from baseline. This reflects a work rate that can be sustained entirely by aerobic metabolism following a brief, initial reliance upon anaerobic energy provision. Based on the description of CP presented in chapter 2 (i.e., the highest power output that can be sustained by aerobic energy supply alone), CP is depicted in figure 3.1 as synonymous with P-LT. By contrast, when exercising at the power output associated with $\dot{V}O_{2max}$ (P-$\dot{V}O_{2max}$), $[La^-]_{bl}$ increases steadily due to an increased reliance on anaerobic glycolysis throughout exercise. It is clear from figure 3.1 that individuals with higher P-LT, CP and $\dot{V}O_{2max}$ values would be working

at a lower relative intensity for any given sub-maximal power output, which would presumably lead to improved endurance exercise performance.
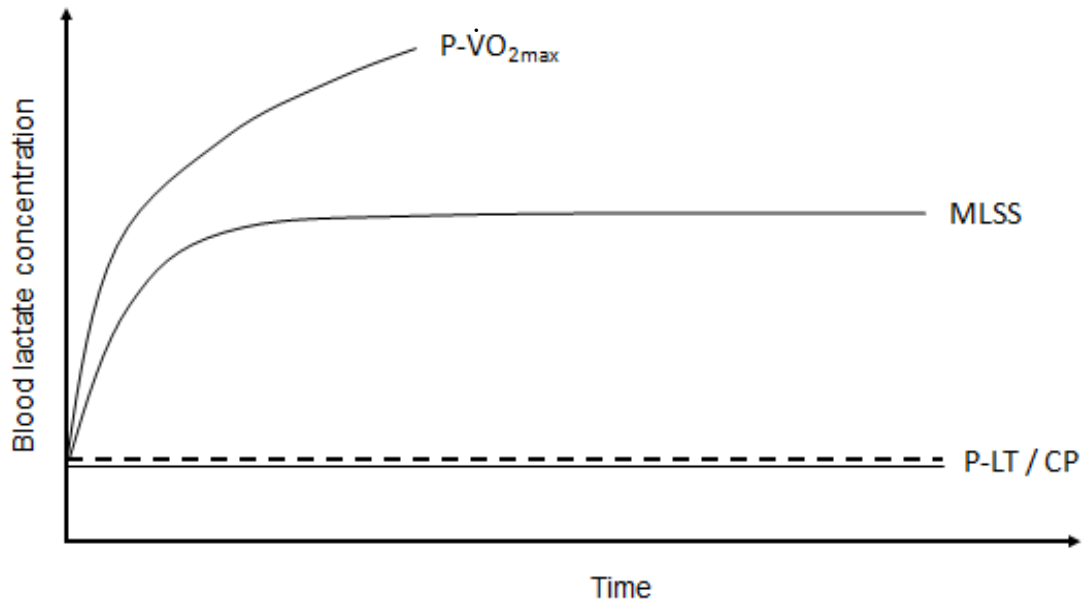


Figure 3.1: A theoretical model of endurance exercise represented by the blood lactate concentration response at the power outputs associated with lactate threshold (P-LT), Critical Power (CP), maximal lactate steady state (MLSS) and $\dot{V}O_{2max}$ (P-$\dot{V}O_{2max}$)

In addition to P-LT, CP and P-$\dot{V}O_{2max}$, the maximal lactate steady state (MLSS), defined as the highest workload that can be maintained without a continuous blood lactate ($La^-_{bl}$) accumulation over time (Beneke, 1995), has also been included on figure 3.1. The MLSS is reflected by a $[La^-]_{bl}$ response that initially rises above baseline as anaerobic glycolysis is relied upon for energy provision, then stabilises as oxygen consumption is able to meet the energetic demands of the activity and an equilibrium between $La^-_{bl}$ production and clearance is reached. The current chapter will investigate the validity of this model illustrated in figure 3.1, with particular focus on the physiological identity of CP.

## 3.1) An introduction to exercise-intensity domains

According to the $\dot{V}O_2$ and $[La^-]_{bl}$ responses to constant-load exercise, three exercise-intensity domains have been defined by Gaesser and Poole (1996) as moderate, heavy and severe (figure 3.2). As identified by Jones *et al.* (2009), other authors use

different terms to describe essentially the same domains. For example, a "very heavy" domain has been identified to reflect those exercise intensities at which $\dot{V}O_2$ and $[La^-]_{bl}$ are unable to stabilise, but where $\dot{V}O_{2max}$ is not attained (Endo *et al.*, 2007; Neder *et al.*, 2000b; Özyener *et al.*, 2003; Smith & Jones, 2001; Whipp *et al.*, 2005). While the moderate, heavy and severe domains will be described in the current section, the very heavy domain will be re-considered later in this chapter.
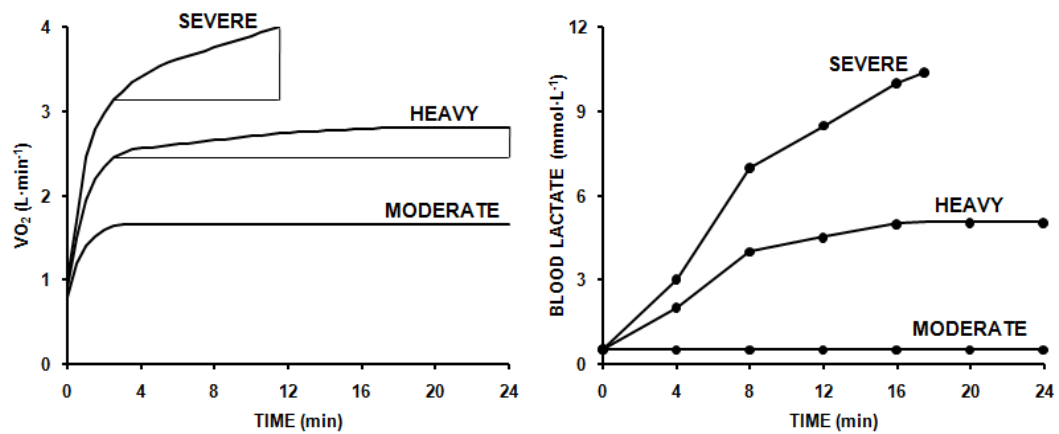


Figure 3.2: The $\dot{V}O_2$ (left panel) and blood lactate concentration (right panel) responses to moderate-, heavy- and severe-intensity exercise; heavy- and severe-intensity exercise can be observed to elicit a $\dot{V}O_2$ slow component (left panel), whereby $\dot{V}O_2$ increases above the expected steady state (re-drawn from Gaesser and Poole, 1996)

*3.1.1) Moderate-intensity exercise*

At the onset of sub-maximal exercise there is a delay in reaching a $\dot{V}O_2$ steady state, so the rate of adenosine triphosphate (ATP) breakdown exceeds the rate of oxidative ATP resynthesis. This has been termed the "oxygen deficit" and is characterised by an immediate reliance upon anaerobic energy sources (i.e., high-energy phosphagens, glycogen and oxygen stored within the active muscles). The lag in oxidative phosphorylation has been identified by $\dot{V}O_2$ kineticists as the primary, or fast, component of the $\dot{V}O_2$ response. During moderate-intensity exercise the $\dot{V}O_2$ kinetics follow a mono-exponential pattern until a steady state in $\dot{V}O_2$ is attained, which occurs within approximately 3 min (Whipp & Wasserman, 1972). Beyond 3 min there is no further change in $\dot{V}O_2$ as the energy demand is easily met by aerobic metabolism.

The oxygen deficit and the subsequent short-term reliance upon anaerobic metabolism may lead to an initial rise in $[La^-]_{bl}$ during moderate-intensity exercise but this returns to baseline levels (or below) as oxygen supply is able to match (and exceed) the demand. The upper boundary of the moderate-intensity exercise domain is demarcated by the LT. Since there is very little disturbance to metabolic processes, exercise within the moderate-intensity exercise domain is identified as "steady state".

*3.1.2) Heavy-intensity exercise*

During heavy-intensity exercise the time taken to attain a steady state in $\dot{V}O_2$ is delayed due to the appearance of an additional $\dot{V}O_2$-SC (Whipp, 1994). As a result, the actual $\dot{V}O_2$ at steady state exceeds that predicted from the sub-LT $\dot{V}O_2$-workload relationship. Nevertheless, heavy-intensity exercise does allow $\dot{V}O_2$ to stabilise as long as the exercise duration is sufficiently long (Poole *et al.*, 1988). The $[La^-]_{bl}$ is elevated during heavy-intensity exercise but rather than continuing to increase over time, it stabilises at around $2 - 5$ mmol·L$^{-1}$ (Jones & Doust, 2001) as the rate of lactate production is balanced by the rate of clearance. Since MLSS reflects the highest workload without a continuous $La^-_{bl}$ accumulation over time, it may be reasoned that the upper boundary of the heavy-intensity exercise domain is demarcated by MLSS.

*3.1.3) Severe-intensity exercise*

During severe-intensity exercise the $\dot{V}O_2$-SC is again evident but the energy demand is greater than that experienced during heavy-intensity exercise. Although aerobic metabolism attempts to match the energy demand, the intensity is too great for $\dot{V}O_2$ to attain a steady state and $\dot{V}O_{2max}$ is reached, unless exercise is terminated before this occurs (Gaesser & Poole, 1996). The lower and upper boundaries of the severe-intensity exercise domain represent the lowest and highest work rates, respectively, at which $\dot{V}O_{2max}$ can be attained (Hill *et al.*, 2002). During severe-intensity exercise the $[La^-]_{bl}$ also continues to rise until exhaustion ensues (figure 3.2, right panel). These metabolic disturbances from homeostasis have led severe-intensity exercise to be described as "non-steady state".

A summary of the responses to moderate-, heavy- and severe-intensity exercise is outlined in table 3.1.

Table 3.1:  Descriptions of the $\dot{V}O_2$ and blood lactate concentration ($[La^-]_{bl}$) responses to moderate-, heavy- and severe-intensity exercise

|  | Moderate | Heavy | Severe |
|---|---|---|---|
| $\dot{V}O_2$ response | Elevated from baseline but stable | Elevated from baseline and exceeds predicted value but stable | Exceeds predicted value, does not stabilise and attains $\dot{V}O_{2max}$ |
| $[La^-]_{bl}$ response | Stabilises at or below baseline values | Elevated from baseline but stable | Continues to rise until exhaustion ensues |

## 3.2) Critical Power relative to the exercise-intensity domains

In section 3.1 it was outlined that the exercise-intensity domains are described by distinct physiological profiles and demarcated by associated physiological parameters. Based upon these physiological characteristics, and with reference to figure 3.1, an exercise-intensity continuum may be described in terms of LT/CP, MLSS and the attainment of $\dot{V}O_{2max}$ (figure 3.3).  While it may be hypothesised that CP would demarcate the moderate- and heavy-intensity exercise domains alongside LT, due to the construct reflecting the upper limit to "purely" aerobic metabolism, the literature does not appear to support this view.  Therefore, the following sections will review this hypothesis.

### 3.2.1) Critical Power and lactate threshold

The linear 2-parameter model described by *equation 1* is based on the concept that any work performed above CP reflects a shift from aerobic metabolism to that involving some anaerobic component and as such, CP was originally thought to correspond to the anaerobic threshold, or AT (Moritani *et al.*, 1981).  Moritani *et al.* (1981) identified AT using the traditional method of a non-linear increase in minute ventilation ($\dot{V}_E$) and carbon dioxide production ($\dot{V}CO_2$) and a systematic increase in $\dot{V}_E/\dot{V}O_2$, without any increase in $\dot{V}_E/\dot{V}CO_2$ (Wasserman *et al.*, 1973).  The method of plotting $\dot{V}CO_2$ against $\dot{V}O_2$ responses to obtain AT has previously been used to reflect LT (Stringer *et al.*, 1992), so it is assumed here that the two measures are

equivalent. Although discussion is beyond the scope of the current literature review, the physiological equivalence of ventilatory and lactate thresholds has been supported for over 40 years (Hollmann, 2001).
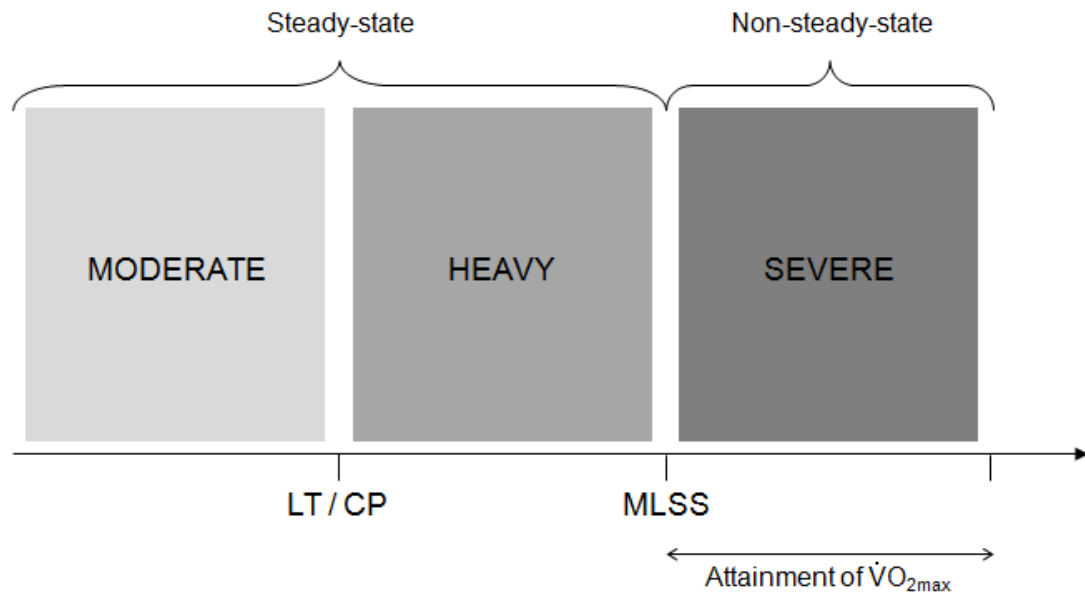


Figure 3.3: A diagrammatical representation of the exercise-intensity domains demarcated by lactate threshold (LT) or Critical Power (CP), maximal lactate steady state (MLSS) and $\dot{V}O_{2max}$

Moritani *et al.* (1981) calculated CP from a series of cycling trials performed to exhaustion (or to < 60 rev·min$^{-1}$) at 275 – 400 W for males and 175 – 300 W for females. Results showed that CP correlated with AT (r = 0.93) and that the $\dot{V}O_2$ values at AT and CP were not significantly different for males (63 ± 7 and 68 ± 8 % of $\dot{V}O_{2max}$, respectively) or females (65 ± 7 and 60 ± 4 % of $\dot{V}O_{2max}$, respectively). The authors concluded that AT and CP were physiologically similar, both representing the maximal rate of work beyond which energy reserves will ultimately be depleted. Subsequent research carried out by deVries *et al.* (1982) reports data for a sub-group of participants (n = 11, rather than n = 16) from those used in the study by Moritani *et al.* (1981). Power outputs at AT and CP were not significantly different (187 ± 13 W versus 170 ± 16 W, respectively) and the two parameters were correlated (r = 0.88). These authors speculated that a single mechanism, or phenomenon, underlies the two parameters.

Despite using similar methods for calculating AT and CP as those used by Moritani *et al.* (1981) and deVries *et al.* (1982), Poole *et al.* (1988) reported significantly greater power output and $\dot{V}O_2$ values at CP (197 W and 2.99 L·min$^{-1}$) compared with AT (120 W and 1.72 L·min$^{-1}$). Similarly, Okudan and Gökbel (2006) reported CP to represent a higher work rate (168 W and 85 % of $\dot{V}O_{2max}$) than AT (106 W and 57 % of $\dot{V}O_{2max}$). The reasons for the discrepancies between the early work of Moritani *et al.* (1981) and deVries *et al.* (1982), and the later studies presented here, are unclear. A low estimate of CP would not be expected in either of the earlier studies since the TTE trials used for modelling CP were < 5 min for all participants (that is, the relatively short-duration TTE trials would over-estimate, rather than under-estimate, CP; see section 2.2.2). The relatively low $\dot{V}O_2$ at CP reported by Moritani *et al.* (1981) for both males and females may be an artefact of estimation, rather than direct measurement, whereby $\dot{V}O_2$ at CP was calculated using the linear regression equation obtained during an incremental test. Alternatively, the discrepancies may be due to differences in the recovery times imposed between CP-determination trials. For example, Poole *et al.* (1988) and Okudan and Gökbel (2006) prescribed exhaustive trials on separate days, whereas Moritani *et al.* (1981) and deVries *et al.* (1982) calculated CP from four trials performed on the same day with only around 30 min of recovery time between trials (i.e., long enough to allow HR to return to within 5 beats·min$^{-1}$ of the resting value). Any residual fatigue (either physiological or psychological) still present after the short recovery periods would decrease the TTE and possibly the CP estimate, perhaps leading to a value similar to AT.

Given that the more recent evidence presented in the current section shows CP to over-estimate AT or LT, coupled with the fact that Moritani *et al.* (1981) and deVries *et al.* (1982) reported data for the same participants, it is perhaps likely that the physiological mechanisms underlying CP are different from those underlying AT or LT.

*3.2.2) Critical Power and maximal lactate steady state*

At the start of the current chapter MLSS was defined as the highest workload that can be maintained without a continuous accumulation of La$^{-}_{bl}$ over time and the MLSS

parameter has been identified as eliciting higher power output and $[La^-]_{bl}$ values than those associated with LT (Haverty *et al.*, 1988; Jones & Doust, 1998). Although not directly linked with $[La^-]_{bl}$, CP was described in section 2.1.2 to correspond to the maximum rate that a given muscle can sustain for a very long time without fatigue. It is perhaps due to the potentially comparable physiology underlying exercise at CP and MLSS that led to investigations into the relationships between the two parameters.

McLellan and Cheung (1992) found CP to occur at a significantly higher power output than MLSS, which they defined as individual anaerobic threshold (IAT)[2], reporting values of 265 and 235 W for CP and IAT within active males, respectively. They also reported CP to reflect a significantly higher $\dot{V}O_2$ and % of $\dot{V}O_{2max}$ (3.35 L·min$^{-1}$ and 82 %, respectively) compared with the values elicited at IAT (2.97 L·min$^{-1}$ and 72 %, respectively). Similarly, Pringle and Jones (2002) compared MLSS with CP for untrained participants and showed the two parameters to differ (222 and 242 W for MLSS and CP, respectively). These absolute power output values corresponded to 65 and 71 % of P-$\dot{V}O_{2max}$, respectively. Despite a significant difference between CP and MLSS, the two parameters were strongly correlated (r = 0.95). Dekerle *et al.* (2003) also demonstrated higher absolute and relative values for CP (278 W and 85 % of $\dot{V}O_{2max}$) compared with MLSS (239 W and 74 % of $\dot{V}O_{2max}$) using trained individuals. However, the relationship between the two parameters was weak (r = -0.11). This inconsistency with the results of Pringle and Jones (2002) does not appear to be due to methodological factors, since both studies used four trials lasting 2 – 15 min to determine CP and calculated MLSS as the highest work rate that could be maintained for 30 min without an increase in $[La^-]_{bl}$ of > 1 mmol·L$^{-1}$ within the final 20 min (Beneke, 1995). Furthermore, MLSS was determined using similar levels of precision, with successive constant-load tests differing by ~ 5 – 6 % of P-$\dot{V}O_{2max}$. The weak correlation identified between the two parameters in the study by Dekerle *et al.* (2003) may be a consequence of homogeneity within the participant group, which would prevent a wide spread of data points and potentially conceal any existing relationship.

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[2] McLellan and Cheung (1992) used the term IAT to reflect a metabolic rate where the elimination of lactate from the blood is maximal and equal to the rate of diffusion of lactate from the exercising muscle to the blood. They derived the IAT from a single incremental exercise test and proposed that it provides a measure of an individual's maximal lactate steady state, or MLSS.

The data presented in the current section indicate that, when confining the evidence to studies that have used cycle ergometry, CP appears to exceed MLSS (Dekerle *et al.*, 2003; McLellan & Cheung, 1992; Pringle & Jones, 2002). This is not consistent with the models proposed in figures 3.1 and 3.3, but instead suggests that CP may reflect an exercise intensity that lies beyond the heavy-intensity exercise domain. This possibility will be investigated in the next section, with a review of the literature reporting direct physiological responses to exercise at and around CP.

**3.3) Responses to exercise at and above Critical Power**

*3.3.1) Time to exhaustion during exercise at Critical Power*

A wide range of durations have been reported for exhaustive exercise at CP, from 16 min to more than 60 min (table 3.2). This is despite similar protocols being used for CP determination (around 3 – 5 exhaustive trials lasting between 1 and 10 min), homogenous characteristics of participants (young, active and predominantly male) and the exercise mode being restricted to cycle ergometry. In addition to the studies outlined in table 3.2, Scarborough *et al.* (1991) identified considerable inter-individual variability in TTE at CP during cycle-ergometer exercise using female college students, with values ranging from 15 to 90 min; the latter duration may have been greater still, except that exercise was terminated by the experimenters after 90 min. More recently, de Lucas *et al.* (2002) have reported that two out of 14 competitive cyclists were exhausted during track-cycling exercise at CP after only ~ 18 min, while eight were able to complete the prescribed exercise of 30 min at CP. In addition, Bull *et al.* (2000) reported that one out of nine healthy males was unable to continue cycling at CP beyond 20 min while five were able to complete the full 60-min protocol.

Table 3.2: A summary of data for studies that have used young, healthy participants to investigate the responses to cycle ergometry exercise at Critical Power listed according to whether exercise was steady state or not

| Reference | Cycle ergometer | Number of exhaustive trials | Duration of exhaustive trials | TTE at CP (min) | $\dot{V}O_2$ at end of exercise at CP (% of $\dot{V}O_{2max}$) | $\Delta[La^-]_{bl}$ during exercise at CP (mmol·L$^{-1}$) | Exercise at CP: steady state or not? |
|---|---|---|---|---|---|---|---|
| Poole *et al.* (1990) [a] | E, Mijnhardt KEM-2 | ≥ 5 | 1 – 10 min | > 24 | 79 | NS | Steady state |
| Poole *et al.* (1990) [b] | E, Mijnhardt KEM-2 | ≥ 5 | 1 – 10 min | > 24 | 79 | NS | Steady state |
| Hill & Smith (1999) [c] | E, Mijnhardt 800S | 3 | 1 – 9 min | 51 | 80* | NR | Steady state |
| Hill & Smith (1999) [d] | E, Mijnhardt 800S | 3 | 1 – 9 min | 65 | 80* | NR | Steady state |
| Hill *et al.* (2002) | E, Mijnhardt 800S | 3 or 4 | 2 – 9 min | > 25 | 91 | NR | Steady state |
| Overend *et al.* (1992) | E, Lode | 4 | 2 – 20 min | > 24 | 85 | 0.4 | Inconclusive |
| Vautier *et al.* (1995) | F, Monark 864 | ≤ 5 | 3.5 – 35 min | 49 | *($\dot{V}O_2$ drift: 5.33 mL·min$^{-1}$)* | *($NS_{SS}$)* | Inconclusive |
| McLellan & Cheung (1992) | E, Ergomed 930 | 5 | *(90 – 120 %$\dot{V}O_{2max}$)* | 21 | 87 | 1.8 | Not steady state |
| Brickley *et al.* (2002) | F, Monark with SRM | 3 | 1 – 10 min | 30 | 91 | 2.2 | Not steady state |
| Baron *et al.* (2005) | E, Ergometrics 800 | 4 | *(90 – 110 %$\dot{V}O_{2max}$)* | 22 | 91 | 3.8 | Not steady state |
| Carter *et al.* (2005) | E, SRM | 3 | 2 – 15 min | 16 | 97[†] | 3.2 | Not steady state |

TTE = time to exhaustion; $\Delta[La^-]_{bl}$ = change in blood lactate concentration from ~ 10 min until the end of exercise; steady state or not? = as concluded by the authors; E = electrically-braked; F = friction-braked; NS = non-significant; NR = not reported; [SS] = not different from lactate steady state; [a] pre-training; [b] post-training; [c] trial 1; [d] trial 2; * $\dot{V}O_2$ estimated by linear regression; [†] not significantly different from $\dot{V}O_{2max}$

The apparently large inter-individual and inter-study variability for TTE at CP within homogenous groups is probably due to the sensitivity of t for low P (i.e., the hyperbolic nature of the P-t relationship), whereby any small error or change in the estimate or application of CP would significantly alter the TTE. Furthermore, it highlights the importance of tightly controlling CP determination methods and ensuring consistency in protocols both within and across experimental studies, in order to obtain comparable and physiologically valid data. It also emphasises the need for reliable and accurate power output measurements when using cycle ergometer exercise.

Performance at CP appears to be subject to learning effects and it may be that variability could be reduced by introducing familiarisation trials. For example, Scarborough *et al.* (1991) reported TTE at CP to increase by an average of 7.9 min from the first (42.9 ± 6.6 min) to a second (50.8 ± 6.9 min) exhaustive trial at CP. Similarly, Hill and Smith (1999) found exhaustive exercise at CP to last 51 min on a first trial and 65 min on a second trial. Furthermore, Bishop and Jenkins (1996) found that exercise at CP increased by 4.2 min, from 22.2 to 26.4 min, in the control group within their 6-week training study. These increases in TTE at CP of ~ 18 – 27 % would presumably, if due to learning effects, be reduced by familiarising participants to long-duration TTE trials.

*3.3.2) Responses to exercise at Critical Power*

The theoretical basis for the CP construct implies that exercise at CP would be fuelled entirely by aerobic energy production and, as such, would be sustained for a very long period of time. However, as outlined in section 3.3.1, this does not appear to be the case as TTE at CP is relatively short (i.e., often < 1 h). This reality may be due to limitations of the model. For example, it is reasoned that exhaustive exercise trials lasting 3 – 15 min completely deplete anaerobic energy stores, thereby producing an asymptotic parameter estimate that reflects the upper limit of power production that is exclusively aerobic. However, anaerobic energy stores do not deplete fully during short, high-intensity exercise; for example, muscle ATP and phosphocreatine (PCr) concentrations have been shown to reduce by only 30 and 60 %, respectively,

following 3 min of exhaustive, constant-load exercise (Bangsbo *et al.*, 1990). Moreover, exercise lasting 3 – 15 min appears to obtain > 60 % of the required energy from aerobic metabolism (Gastin, 2001), thus preserving anaerobic energy sources. These observations reflect the complex integration of energy provision during intense exercise and imply that the derivation of independent aerobic and anaerobic capacities from CP modelling is not externally valid.

Results from four key studies that have investigated the responses to exercise at CP have concluded that CP reflects an intensity eliciting a physiological steady state. That is, $\dot{V}O_2$ at the end of exercise (either measured directly or estimated by linear regression) was significantly lower than $\dot{V}O_{2max}$ and $[La^-]_{bl}$ did not rise significantly towards the end of exercise (Hill *et al.*, 2002; Hill & Smith, 1999; Poole *et al.*, 1988; Poole *et al.*, 1990). Data from three of these studies are shown in table 3.2; the study by Poole *et al.* (1988) has not been included since the participants were the same as those used in a later study by three of the same authors (Poole *et al.*, 1990). However, it is noted that Poole *et al.* (1988) reported stabilisation of $\dot{V}O_2$, $[La^-]_{bl}$, extracellular bicarbonate concentration ($[HCO_3^-]$) and blood pH ($pH_{bl}$) after around 16 – 20 min of exercise at CP. This led the authors to conclude that CP may represent MLSS, a notion that was not supported in section 3.2.2 of the current literature review due to direct comparisons showing CP to represent an exercise intensity greater than MLSS (Dekerle *et al.*, 2003; Pringle & Jones, 2002).

Contrary to the results of Poole *et al.* (1988; 1990), Hill and Smith (1999) and Hill *et al.* (2002), a number of authors have shown $\dot{V}O_2$, $[La^-]_{bl}$ and $[HCO_3^-]$ to continue to rise, and $pH_{bl}$ to continue to decrease, during exercise at CP (Baron *et al.*, 2005; Brickley *et al.*, 2002; Carter *et al.*, 2005; McLellan & Cheung, 1992). These studies are also summarised in table 3.2 and show increases in $[La^-]_{bl}$ of between 1.8 and 3.8 mmol·L$^{-1}$ and end $\dot{V}O_2$ values of more than 87 % of $\dot{V}O_{2max}$. Furthermore, increases in $\dot{V}O_2$ from ~ 5 min to the end of exercise at CP (i.e., the $\dot{V}O_2$-SC) were reported as 0.3 to 2.4 L·min$^{-1}$. These findings indicate that exercise at CP reflects a non-steady state and that the associated fatigue is coupled with a continued deviance from physiological homeostasis. While this idea potentially supports the concept of a very heavy-intensity exercise domain, which was introduced at the start of section 3.1, the

notion that CP identifies a boundary to this domain, as purported by a number of researchers (Endo *et al.*, 2007; Neder *et al.*, 2000b; Smith & Jones, 2001; Whipp *et al.*, 2005), is not necessarily supported.

The reasons for the disagreement between studies are unclear. All authors used similar modelling methods to estimate CP using a two-parameter model. Furthermore, modelling techniques would not explain between-participant differences identified within the same experimental studies. Again, the differences in results may be due to the sensitivity of responses to exercise around the asymptote of the P-t relationship. That is, slight inaccuracies in the measurement of power output or work done during the TTE trials, or slight deviations from the prescribed exercise intensity at CP, may result in large differences when measuring the responses to exercise at CP. These inconsistent data in the literature again highlight the importance of standardising the methods for estimating CP and ensuring accuracy when prescribing exercise at CP.

*3.3.3) Responses to exercise above Critical Power*

Only four studies appear to have directly measured CP and the responses to exercise above CP using cycle ergometer exercise (Hill *et al.*, 2002; Jones *et al.*, 2008; Poole *et al.*, 1988; Poole *et al.*, 1990). Based on the notion that CP reflects the boundary between the heavy- and severe-intensity exercise domains, all of these authors theorised that exercising slightly above CP would elicit inexorable increases in $\dot{V}O_2$, $[La^-]_{bl}$ and/or inorganic phosphate concentration ($[P_i]$) to the limit of exercise tolerance. As discussed in section 3.3.2, however, a number of studies have shown exercise at CP to represent a non-steady state and for CP, therefore, to represent an exercise intensity that lies beyond the heavy-intensity exercise boundary (Baron *et al.*, 2005; Brickley *et al.*, 2002; Carter *et al.*, 2005; McLellan & Cheung, 1992). On this basis, exercising at an intensity slightly greater than CP would also be expected to lead to continued increases in respiratory and metabolic temporal profiles to the point of exhaustion; however, no further insight into the physiological basis for CP, per se, would be gained from this knowledge.

Indeed, both Poole and colleagues and Hill and colleagues found that $\dot{V}O_2$ increased during exercise above CP (i.e., at ~ 105 % of CP) until it attained a value not different from $\dot{V}O_{2max}$ (Hill *et al.*, 2002; Poole *et al.*, 1988; Poole *et al.*, 1990). In addition, $[La^-]_{bl}$, $[HCO_3^-]$ and $pH_{bl}$ did not stabilise during exercise above CP (Poole *et al.*, 1988; Poole *et al.*, 1990). Jones *et al.* (2008) used phosphorous-31 magnetic resonance spectroscopy ($^{31}P$-MRS) and reported exercise above CP (i.e., at ~ 110 % of CP) to result in continuous reductions in the muscle PCr concentration ([PCr]) until exhaustion ensued. By contrast, exercise below CP (i.e., at ~ 90 % of CP) produced an initial fall in the muscle [PCr], but then a plateau followed prior to exhaustion. All of the studies mentioned in the current paragraph concluded that CP demarcates the boundary between stable and unstable physiological environments. However, since a number of studies have presented evidence to the contrary, and since Jones *et al.* (2008) did not actually measure muscle metabolic responses to exercise at CP, this conclusion seems rather vulnerable.

*3.3.4) Responses to exercise below Critical Power*

No research appears to have directly compared the responses to exercise at and below CP. The comparisons made by Pringle and Jones (2002) and Dekerle *et al.* (2003) between MLSS and CP suggest that exercise slightly below CP would elicit a steady state in $[La^-]_{bl}$. Furthermore, the plateau in [PCr] attained during exercise 10 % below CP presents further evidence that exercise slightly below CP reflects a physiological steady state (Jones *et al.*, 2008). However, additional research is required in order to test this hypothesis.

**3.4) Summary**

At the start of the current chapter CP was outlined as a construct that reflects the highest power output that is dependent only on aerobic energy supply. As such, CP was included alongside LT in the models of endurance and the exercise-intensity domains. However, throughout this detailed review of the literature it has become evident that CP appears to reflect a work rate that is greater than MLSS and, therefore, P-LT. It may be argued that plotting P-t co-ordinates from exhaustive, severe-

intensity exercise lasting 3 – 15 min would provide an asymptotic parameter estimate that is reflective of the lower boundary of severe-intensity exercise. Indeed, a number of authors have described CP as demarcating the boundary between the heavy- and severe-intensity domains, or as the intensity boundary above which $\dot{V}O_{2max}$ will be elicited during exercise of sufficient duration (Hill *et al.*, 2002; Hill & Smith, 1999; Jones & Doust, 2001; Poole *et al.*, 1988; Poole *et al.*, 1990; Smith & Jones, 2001). However, while CP is frequently described as reflecting a steady-state exercise intensity, it has become evident that such an explanation is probably imprudent. Perhaps CP lies somewhere within the severe-intensity exercise domain, rather than at the lower boundary. Or perhaps CP is better characterised through the very heavy-intensity exercise domain. In reality there appear to be two schools of thought: one stating that exercise at CP reflects a steady state and one stating that exercise at CP reflects a non-steady state. Updated versions of figures 3.1 and 3.3 are presented in figures 3.4 and 3.5, based on the literature presented within the current chapter. One of the purposes of the present thesis will be to better understand the controversy surrounding the physiological characteristics of exercise at CP.
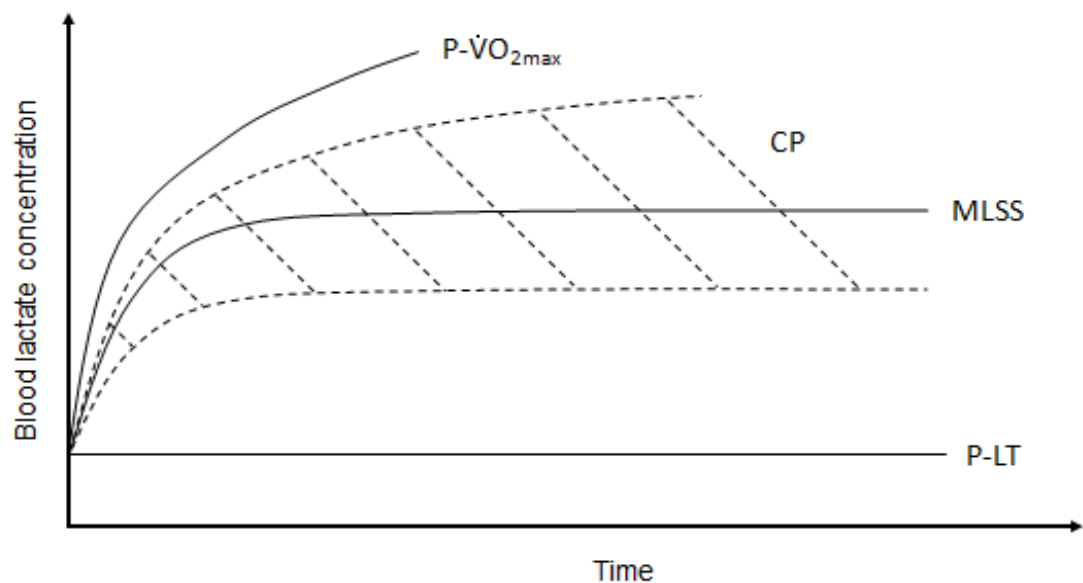


Figure 3.4: A revised theoretical model of endurance exercise represented by the blood lactate response to exercise at the power outputs associated with lactate threshold (P-LT), maximal lactate steady state (MLSS), Critical Power (CP) and $\dot{V}O_{2max}$ (P-$\dot{V}O_{2max}$)
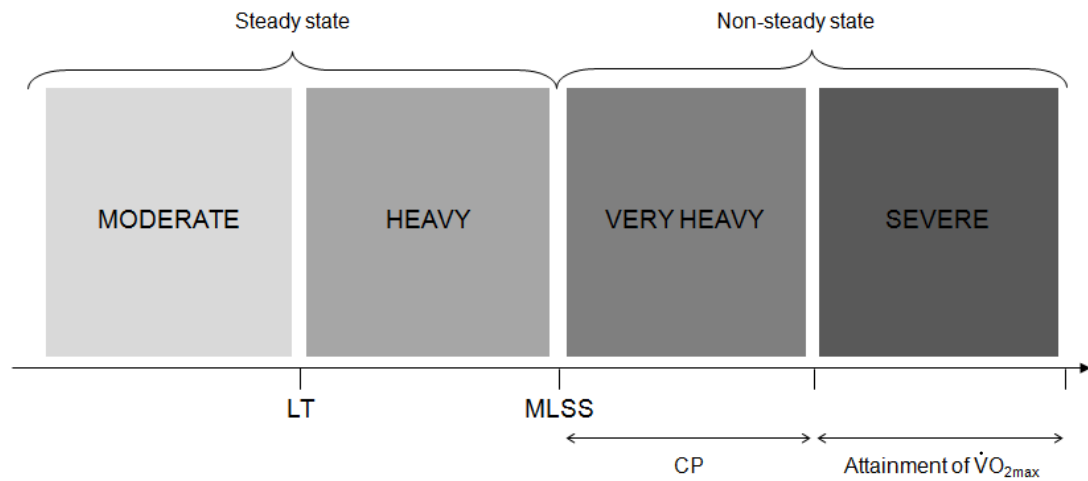
Figure 3.5: A revised diagrammatical representation of the exercise-intensity domains characterised by lactate threshold (LT), maximal lactate steady state (MLSS), Critical Power (CP) and $\dot{V}O_{2max}$

# 4) Review of the Relevant Literature: The Application of Critical Power to Performance and Training

## 4.1) Exercise modes and population groups

### *4.1.1) Critical Power and exercise modes*

The CP concept was originally developed for synergic muscle groups including the quadriceps femoris, biceps brachii and triceps brachii (Monod & Scherrer, 1965; Scherrer *et al.*, 1954). Only sometime later was the concept extended to whole body exercise using cycle ergometry (Moritani *et al.*, 1981). Aside from cycling, a Critical Running Speed (CRS) has been introduced for running exercise (Kolbe *et al.*, 1995), whereby power or work done is substituted for velocity or distance, respectively, in any of the CP relationships *(equations 1 – 3)*. While it is worth acknowledging here that CRS has been applied to intermittent running, whereby the exhaustive trials consist of high-intensity work followed by brief rest periods (Buchheit *et al.*, 2008; Dupont *et al.*, 2002; Kachouri *et al.*, 1996; Morton & Billat, 2004), intermittent running will not be discussed in this review of literature due to the complexities of metabolic and physiological recovery kinetics during the rest periods.

The physiological responses to exercise at CRS have been reported to a lesser extent than CP, but findings appear similar. For example, Bull *et al.* (2008) have shown exercise at CRS (estimated from the three, 2-parameter models) to last between 13 and 60 min (at which point the investigators terminated the trials). In addition, the $\dot{V}O_2$ -SC values (measured from 3 min to the end of exercise) ranged between 0.44 and 0.46 $L \cdot min^{-1}$, which are similar to the lower values highlighted in section 3.3.2 for non-steady state cycling at CP. Lin and Wang (1999) support the notion that exercise at CRS reflects a physiological non-steady state, reporting increases over time in HR, $\dot{V}E$, $\dot{V}O_2$, $\dot{V}CO_2$, rectus femoris iEMG and $[La^-]_{bl}$. They also observed physiological responses to exercise below CRS (i.e., at 85 %) and found no changes in $\dot{V}E$, $\dot{V}O_2$ or $[La^-]_{bl}$ over time, thus concluding a steady state.

In contrast to both of these studies, and the conclusion in section 3.2.2 (i.e., that CP exceeds MLSS for cycle ergometry), Smith and Jones (2001) showed no significant difference between CRS and the velocity associated with MLSS (v-MLSS) during treadmill running (14.4 versus 13.8 km·h$^{-1}$, respectively). This was despite using similar protocols for CRS determination (i.e., three or four exhaustive trials lasting 2 – 12 min) and MLSS (i.e., an increase in [La$^-$]$_{bl}$ of < 1 mmol·L$^{-1}$ in the final 20 min of a 30-min constant-load trial) as those used in the two cycling studies that compared CP and MLSS (Dekerle *et al.*, 2003; Pringle & Jones, 2002). The differences may suggest a higher [La$^-$]$_{bl}$ at MLSS during running compared with cycling exercise. However, this is not supported by Beneke and von Duvillard (1996), who reported higher [La$^-$]$_{bl}$ values at MLSS in activities that use lower total muscle masses and higher forces of the dominant muscles (e.g., cycling). It is worth acknowledging that, although v-MLSS and CRS appeared equivalent for running, Smith and Jones (2001) presented 95 % limits of agreement that were too great for the two parameters to be used interchangeably. Therefore, further studies using running exercise are required to clarify the physiological characteristics of CRS.

In addition to cycling and running exercise, the CP concept has also been developed for and applied to rowing (Kennedy & Bell, 2000), kayaking (Clingeleffer *et al.*, 1994) and swimming (Wakayoshi *et al.*, 1992). Conflicting results from two swimming studies provide equivocal conclusions, showing Critical Swimming Speed (CSS) to be either equivalent to (Wakayoshi *et al.*, 1993), or greater than (Dekerle *et al.*, 2005), v-MLSS. Since similar populations were used for the two studies (i.e., trained, male swimmers), it is likely that the different testing procedures would account for the discrepancies in the results. Wakayoshi *et al.* (1993) calculated CSS from two short trials (with mean durations of 2.1 and 4.4 min) and compared the [La$^-$]$_{bl}$ responses during three, 4 x 400-m swims at 98, 100 and 102 % of CSS, in order to identify v-MLSS. The authors found [La$^-$]$_{bl}$ to reach a steady state of 3.2 mmol·L$^{-1}$ during the 4 x 400-m trial at 100 % of CSS and concluded that this reflected v-MLSS. However, it is likely that the rest periods following each 400-m period suppressed the rise in [La$^-$]$_{bl}$ considerably, compared with a 1600-m continuous swim (which would be a more conventional method of calculating MLSS). Had the 1600 m of swimming been continuous, the [La$^-$]$_{bl}$ steady state would probably have occurred at an intensity below 100 % of CSS. The results of Dekerle *et al.* (2005) may be considered more

valid, since both v-MLSS and CSS were assessed using traditional methods (i.e., three or four 30-min trials to determine v-MLSS and four trials lasting between 1.6 and 7.1 min to estimate CSS).

In summary, the few studies that have investigated the physiological characteristics of exercise at CP using modes other than cycle ergometry have revealed inconclusive results. In order to make valid comparisons between MLSS and CRS or CSS, controlled experiments using consistent methods for assessing each parameter is needed. Additional measurements of the physiological responses to exercise at CRS and CSS are also required to gain a deeper understanding of these parameters with respect to the exercise-intensity domains across different modes of exercise.

*4.1.2) Critical Power in different population groups*

The majority of research that has investigated the physiological characteristics of CP using cycle ergometry has been carried out using young (i.e., < 30 y), healthy, predominantly male participants (Baron *et al.*, 2005; Brickley *et al.*, 2002; Hill *et al.*, 2002; Jenkins & Quigley, 1990; Poole *et al.*, 1988; Pringle & Jones, 2002). Consequently, the physiological responses to exercise at and around CP across more diverse population groups are less well-understood. A descriptive review is provided by Leclair *et al.* (2008b), which presents CP data for participant groups categorised according to training status, sex, age and disease. The application of CP in training will be presented in section 4.3 and there is little comparative research for males versus females. As such, the current section of this literature review will focus upon population groups categorised by age (i.e., young adults versus elderly) and health status (i.e., disease versus healthy). Exploring beyond the resource of Leclair *et al.* (2008b), the metabolic responses to exercise at CP and the relationships between CP and other endurance parameters (i.e., LT and $\dot{V}O_{2max}$) will be discussed. Although CP has been applied to child populations, particularly in recent years (Berthoin *et al.*, 2003; Berthoin *et al.*, 2006; Dekerle *et al.*, 2009; Denadai *et al.*, 2000; Fawkner & Armstrong, 2002; Greco *et al.*, 2002; Greco & Denadai, 2005; Leclair *et al.*, 2008a; Toubekis *et al.*, 2006; Williams *et al.*, 2008), the differences in child and adult physiology are outside the focus of this thesis.

*Young versus elderly adults*

Overend *et al.* (1992) conducted an in-depth study comparing the physiological responses of young (20 – 35 y) and elderly (> 65 y) active males during exercise at CP.   Although each group of individuals was involved in similar amounts of recreational physical activity, the young group elicited significantly greater CP and P-$\dot{V}O_{2max}$ values (177 ± 10 and 286 ± 14 W, respectively) compared with the elderly group (115 ± 9 and 172 ± 14 W, respectively).  This is consistent with research that has shown aerobic power to decline with age (Rogers *et al.*, 1990).  By contrast, however, CP was significantly greater for the elderly group compared with the young group when expressed as a % of P-$\dot{V}O_{2max}$ (70 ± 1 versus 62 ± 2 % of P-$\dot{V}O_{2max}$, respectively).  Furthermore, the $\dot{V}O_2$ attained during a 24-min exercise bout at CP was significantly greater (relative to $\dot{V}O_{2max}$) in the elderly group compared with the young group (92 ± 2 versus 85 ± 2 % of $\dot{V}O_{2max}$, respectively).  Despite the higher relative intensity of exercise at CP in the elderly group, $\dot{V}O_2$ and $[La^-]_{bl}$ were stable at the end of the 24-min bout at CP.  Conversely, $[La^-]_{bl}$ (but not $\dot{V}O_2$) continued to rise at the end of exercise at CP within the younger group.  It would appear that, despite $\dot{V}O_2$ at CP lying closer to $\dot{V}O_{2max}$ in active, elderly males, exercise at CP reflects a physiological steady-state within this population group.   However, this is not necessarily the case within younger, active males.

Neder *et al.* (2000b) presented similar findings in a group of sedentary, elderly (60 – 75 y) males compared with young (< 30 y) males.  That is, absolute CP and P-$\dot{V}O_{2max}$ values were lower for the elderly group (104 and 159 W for CP and P-$\dot{V}O_{2max}$, respectively) versus the young group (197 and 288 W for CP and P-$\dot{V}O_{2max}$, respectively) but $\dot{V}O_2$ during exercise at CP expressed as a percent of $\dot{V}O_{2max}$ was higher in the elderly group (88 versus 79 % of $\dot{V}O_{2max}$).  In addition to CP and $\dot{V}O_{2max}$, LT was also measured in both groups and was lower in the elderly group when expressed in L·min$^{-1}$ (1.17 versus 1. 72 L·min$^{-1}$), but was higher when expressed relative to $\dot{V}O_{2max}$ (62 versus 45 % of $\dot{V}O_{2max}$).  These results are illustrated in figure 4.1, where the upper limits of the solid white, solid black and criss-cross areas represent the $\dot{V}O_2$ at LT, $\dot{V}O_2$ at CP and $\dot{V}O_{2max}$, respectively.   If these

physiological markers represent the upper boundaries of the moderate-, heavy- and severe-intensity exercise domains, then it is clear from figure 4.1 that the elderly group has smaller absolute exercise-intensity ranges within all three domains (left chart), as well as compressed relative ranges for the heavy (solid black) and severe (criss-cross) domains (right chart). This could be due to a reduction in fast-twitch muscle fibre area with age, irrespective of training status (Proctor *et al.*, 1995), which would lead to a relative decline in the ability to sustain higher work rates.
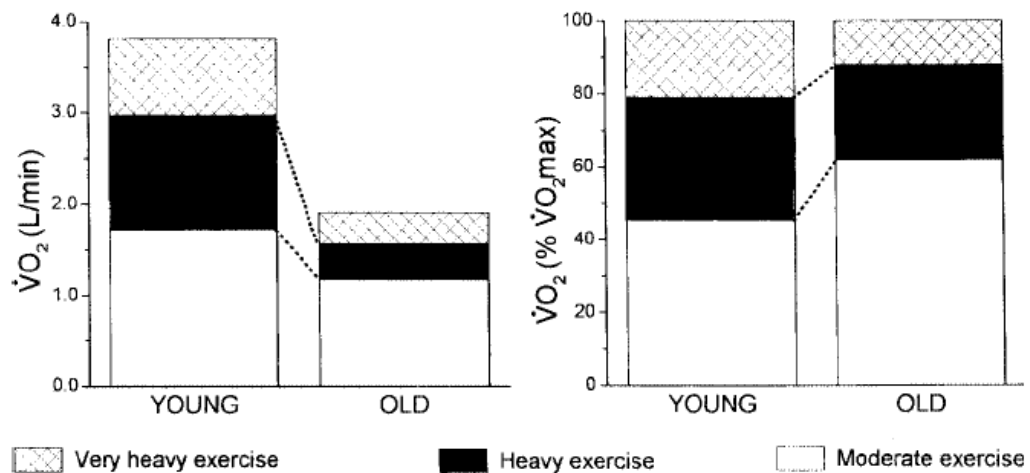


Figure 4.1: Effects of ageing on the absolute (left chart) and relative (right chart) ranges of the exercise-intensity domains in sedentary males; the upper limits to the moderate, heavy and severe exercise intensities are reflective of $\dot{V}O_2$ at LT, $\dot{V}O_2$ at CP and $\dot{V}O_{2max}$, respectively (taken from Neder *et al.*, 2000*b*)

The data from Neder *et al.* (2000b) allows an approximation of $\dot{V}O_2$ at CP to be calculated as a % of $\Delta$, where $\Delta$ is the difference between $\dot{V}O_2$ at LT and $\dot{V}O_{2max}$. For example, steady-state $\dot{V}O_2$ at CP was 2.97 L·min$^{-1}$ for the young group and, since the $\dot{V}O_2$ at LT and $\dot{V}O_{2max}$ were 1.72 and 3.81 L·min$^{-1}$, respectively, $\dot{V}O_2$ at CP $\approx$ [(2.97 – 1.72) / (3.81 – 1.72)] $\approx$ 60 % of $\Delta$. For the older group, $\dot{V}O_2$ at CP was $\approx$ 53 % of $\Delta$. These calculations show that $\dot{V}O_2$ at CP may lie closer to $\dot{V}O_2$ at LT than to $\dot{V}O_{2max}$ in older versus younger individuals. When considered in terms of exercise-intensity domain characteristics, this perhaps helps explain the steady versus non-steady state nature of exercise at CP among older versus younger participants.

A comparison of two studies that have used running exercise (Billat *et al.*, 1998; Billat *et al.*, 2001) may provide some supporting evidence for a lower CP as a % of $\Delta$

in older individuals.  Using treadmill running, Billat *et al.* (1998) found the CRS of young (20 – 33 y) runners to lie at 49 % of $\Delta$ (the % of $\Delta$ value was not reported in the original article, but has been calculated for the purpose of the current literature review using the data provided for individual participants).  By contrast, the CRS of older (46 – 60 y) runners was only 21 % of $\Delta$ (Billat *et al.*, 2001).  These comparisons support the notion that CP (or CRS) is lower as a % of $\Delta$ in older individuals compared with their younger counterparts and, as such, perhaps explain why $\dot{V}O_2$ and $[La^-]_{bl}$ stabilise during exercise at CP in older individuals.  However, since the absolute values for the velocity associated with $\dot{V}O_{2max}$ (v-$\dot{V}O_{2max}$) and $\dot{V}O_{2max}$ differed considerably between groups (v-$\dot{V}O_{2max}$: 22.4 versus 15.9 km·h$^{-1}$ and $\dot{V}O_{2max}$: 74.9 versus 52.1 mL·kg$^{-1}$·min$^{-1}$ for the younger and older groups, respectively), the possibility of aerobic capability rather than age, per se, explaining the higher CP or CRS as a % of $\Delta$ may not be discounted at this stage and more controlled research examining this issue is necessary.

*Healthy versus disease populations*

Few studies have used CP within disease populations and those that have appear to have focused on chronic obstructive pulmonary disease (COPD) patients (Casas *et al.*, 2005; Malaguti *et al.*, 2006; Neder *et al.*, 2000a; Puente-Maestu *et al.*, 2003).  Only one of these studies (Neder *et al.*, 2000a) has investigated responses to exercise at CP by comparing COPD sufferers (8 males aged 69.1 ± 8.5 y) with healthy controls (10 males aged 65.6 ± 4.1 y).  The authors showed that CP was significantly lower in COPD patients versus controls (65 versus 110 W, respectively), but that the $\dot{V}O_2$ at the end of exercise at CP (expressed as a % of $\dot{V}O_{2max}$) was higher in the COPD group (92 versus 84 % of $\dot{V}O_{2max}$).  These data are similar to the age-related comparisons (figure 4.1) and suggest that COPD sufferers have a smaller range of higher exercise intensities within which to function.  Since LT was not measured, CP as a % of $\Delta$ may not be estimated for the two population groups.  However, the $\dot{V}O_2$ responses during exercise at CP implied that, for both groups, a steady-state was attained.  While it appears that CP may demarcate the boundary between the heavy and severe exercise-intensity domains for elderly healthy and COPD populations groups, this possibility requires further research attention.

**4.2) The application of Critical Power to performance**

In order to discuss the application of CP to performance the focus of the literature review will return to cycling exercise, using both field- and laboratory-based cycling. In addition, while a number of applied studies have investigated the validity of the anaerobic and aerobic components of the power- or work-time relationships, it should be re-iterated that only the CP component (and not AWC) will be examined here.

Thus far the literature review has been predominantly concerned with the physiological characteristics of CP. However, perhaps more significant to a coach or athlete is the applicability of CP to performance. In theory, the P-t (or P-t$^{-1}$) relationship is able to predict TTE for any P > CP. Conversely, any P ≤ CP would be infinitely sustainable and as such, exercise performed below CP lies beyond the predictive capability of the model. However, infinite sustainability is clearly unrealistic for any exercise intensity and in fact, research data may be used to predict TTE at a given % of CP for P < CP.

Using four exercise trials to estimate CP from the non-linear 2-parameter model *(equation 2)*, Housh *et al.* (1989) compared the predicted and actual TTE values during constant-load exercise at 79, 97, 120, 140 and 160 % of CP using cycle ergometer exercise. From the data in table 4.1 it can be seen that the predicted and actual TTE values for trials above CP were not significantly different (P > 0.05) and that correlations between the two measures were strong (r > 0.8, P < 0.05). These data support the CP model in predicting performance for P > CP. But the P < CP data also present a potentially useful application. By plotting power output against actual TTE for all five trials shown in table 4.1, Housh *et al.* (1989) found that exercising at 83 % of the original CP estimate would be sustainable for 60 min. This finding may be useful for coaches or practitioners wishing to prescribe sub-maximal training or exercise loads. However, it should be noted that during the trials below CP, exercise was terminated by the experimenters at 60 min if fatigue had not occurred. So, while this guideline of "83 % of CP" could be useful within an applied setting, it may under-estimate the actual exercise intensity that is sustainable for 60 min. Furthermore, the large inter-individual variation in TTE during exercise at P < CP

must be recognised, as it limits the validity of applying average relative work rates to individual exercisers.

Table 4.1: Comparisons between predicted and actual time to exhaustion (TTE) at various power loadings (data adapted from Housh *et al.*, 1989)

| % of CP | Power Output (W) | Predicted TTE | Actual TTE | r |
|---------|------------------|---------------|------------|------|
| 79 ± 4 | 156 ± 35 | *infinite* | 58 ± 9 min | - |
| 97 ± 2 | 191 ± 39 | *infinite* | 33 ± 15 min | - |
| 120 ± 2 | 235 ± 46 | 491 ± 234 s | 428 ± 161 s | 0.89* |
| 140 ± 2 | 276 ± 55 | 216 ± 82 s | 208 ± 71 s | 0.88* |
| 160 ± 3 | 314 ± 60 | 142 ± 57 s | 139 ± 47 s | 0.84* |

Significant correlation: * P < 0.05

Using four TTE trials lasting 1.5 – 10 min to estimate CP from *equation 2*, Smith *et al.* (1999) provide evidence that the CP parameter (expressed in $W \cdot kg^{-1}$) is a valid predictor of cycling time-trial performance over 17- and 40-km distances (r = -0.90 and -0.92, respectively; P < 0.01). Since the durations of the 17- and 40-km time-trials (~ 27 and 60 min, respectively) correspond to exhaustion times that have been reported during exercise at CP (see section 3.3.1), it may be speculated that time-trials over this range of distances are performed at intensities similar to CP. Therefore, those individuals with a greater CP would be expected to maintain a higher average power output over the race course and, assuming similar mechanical efficiency and navigational skills, would complete the race in a shorter time.

As discussed previously, the CP model is particularly sensitive around the asymptote of the P-t relationship, whereby small variations in applied power output will result in large differences in TTE (Vandewalle *et al.*, 1997). Although this leads to a low predictive capability of CP, the two studies discussed in the current section (Housh *et al.*, 1989; Smith *et al.*, 1999) have revealed potential practical uses for CP in terms of predicting performance. For example:

- for exercise intensities where P > CP, TTE may be accurately predicted from the CP model;
- a maximal, exhaustive test lasting ~ 60 min would be achieved at a power output of ~ 85 % of CP;

- CP can predict road cycling time-trial performances over 17 – 40 km, or ~ 27 – 60 min.

## 4.3) Critical Power and training

### 4.3.1) The effect of training on the Critical Power estimate

In order to examine the physiology underpinning the CP construct and the P-t relationship, a small number of studies have investigated the effects of training on the CP estimate, theorising that CP would increase following both continuous and intermittent-type training protocols. The results of these studies are illustrated in figure 4.2, with relative changes in CP plotted against relative changes in $\dot{V}O_{2max}$.
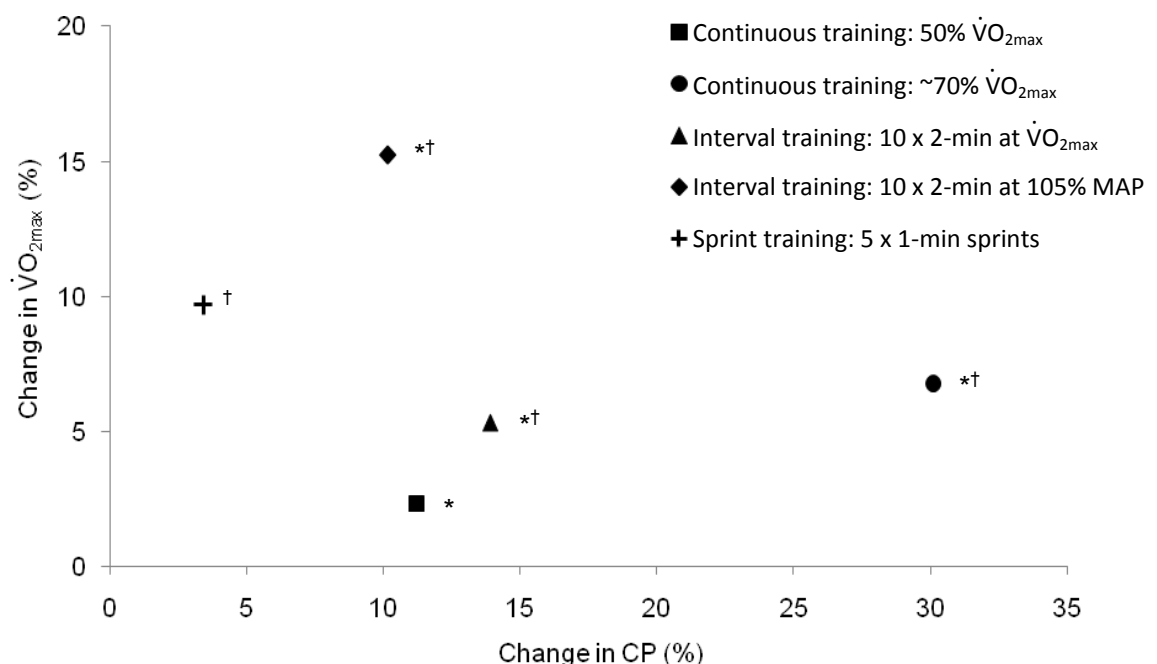
Figure 4.2: The effects of training on changes in Critical Power (CP) and $\dot{V}O_{2max}$
Significant effect of training on: * CP (P < 0.05); † $\dot{V}O_{2max}$ (P < 0.05)

The data in figure 4.2 is derived from four separate studies. Gaesser and Wilson (1988) showed that training three times per week for six weeks using 40 min of relatively low-intensity continuous exercise (50 % of $\dot{V}O_{2max}$; filled square) led to a significant increase in CP (~ 11 %) but no significant increase in $\dot{V}O_{2max}$ (~ 2 %, P > 0.05). By contrast, the same authors found higher-intensity interval training (10 x 2-

min intervals at $\dot{V}O_{2max}$; filled triangle) to produce significant increases in both CP ($\sim$ 14 %) and $\dot{V}O_{2max}$ ($\sim$ 5 %) after six weeks of training three times per week. Jenkins and Quigley (1992) showed that continuous training is able to positively affect both CP and $\dot{V}O_{2max}$, with improvements of around 30 and 7 %, respectively, following 30 – 40 min of continuous training at $\sim$ 70 % of $\dot{V}O_{2max}$ three times per week for eight weeks (filled circle). In addition, 10 x 2-min interval training at 105 % of MAP appears to increase $\dot{V}O_{2max}$ to a greater extent (i.e., $\sim$ 15 %) than interval training at $\dot{V}O_{2max}$, while maintaining improvements in CP ($\sim$ 10 %), as shown by Poole *et al.* (1990) over a period of seven weeks with training three times per week (filled diamond). The results of these three studies confirm that CP may be increased by $\sim$ 10 – 30 % over a period of six to eight weeks using continuous training at moderate and heavy workloads or 2-min intervals close to $\dot{V}O_{2max}$.

Following on from their previous endurance-training study, Jenkins and Quigley (1993) showed that sprint-interval training (5 x 1-min maximal efforts separated by 5-min recovery periods, black cross) performed three times per week for eight weeks did not lead to a significant improvement in CP, but $\dot{V}O_{2max}$ was significantly increased by $\sim$ 10 %. In addition (and not marked on figure 4.2), resistance training performed 3 – 4 times per week over a period of six weeks has been shown to have no significant effect on CP or $\dot{V}O_{2max}$ (Bishop & Jenkins, 1996). In summary, the effect of training on CP appears to be specific to the type of exercise performed during the intervention. Figure 4.2 suggests that CP is most affected by training continuously at an exercise intensity close to CP, but that repeated bouts of sprint or strength exercise, which would rely heavily upon rapid anaerobic energy provision (Gastin, 2001), do not increase the CP parameter estimate. By contrast, $\dot{V}O_{2max}$ increases more profoundly when training intermittently above (but close to) the intensity associated with $\dot{V}O_{2max}$.

The concept proposed here is one of specificity, which states that a particular component of physical fitness must be emphasised in training in order for it to improve (The Oxford Dictionary of Sports Science and Medicine, 2007). This is due to the distinct physiological adaptations that occur when exposed to particular types of

training. For example, continuous sub-maximal exercise training (i.e., below $\dot{V}O_{2max}$) leads to a number of central and peripheral adaptations that enhance aerobic endurance. These adaptations include increases in blood volume and blood flow, stroke volume (SV), maximal cardiac output ($\dot{Q}_{max}$), capillary density, size and density of the mitochondria, aerobic enzymes and fat oxidation, as well as sparing of muscle glycogen, conversion of type IIb muscle fibres to type IIa, reduced rates of lactate ($La^-$) production and enhanced $La^-$ removal (Holloszy & Coyle, 1984; Laursen & Jenkins, 2002; Whyte, 2006). With reference to the data represented in figure 4.2, it may be hypothesised that a combination of these adaptations would improve TTE during CP determination trials, thus resulting in a rightward shift in the P-t profile following training (see figure 2.4). These improvements in aerobic endurance would, therefore, be reflected by an increased CP estimate. By contrast, it is possible that training at 50 % of $\dot{V}O_{2max}$ would fail to present a sufficient stimulus for increasing $\dot{V}O_{2max}$, which relies not only on central adaptations (i.e., increases in blood volume, SV and $\dot{Q}_{max}$), but also on the ability to sustain high-intensity exercise. Additional responses to high-intensity interval training include increases in skeletal muscle buffering capacity and glycolytic enzyme activities, as well as an increased aerobic energy yield (Laursen & Jenkins, 2002; Whyte, 2006). These factors combine with the central and peripheral adaptations listed above to improve the capacity for aerobic metabolism, which would lead to an increased $\dot{V}O_{2max}$. Despite these theories, the precise mechanisms associated with independent changes in CP and $\dot{V}O_{2max}$ are currently unknown and further research is required to unravel the underpinning physiology.

*4.3.2) Physiological responses to training at Critical Power*

In the previous section it was stated that CP appears to be most affected by training continuously at a work rate that is close to CP. This conclusion was based on the work of Jenkins and Quigley (1992), who used a training intervention of ~ 70 % of $\dot{V}O_{2max}$. In their study, in fact, Jenkins and Quigley (1992) proposed a training intervention of 100 % of CP. However, the purpose of their study was not to investigate CP as a training stimulus, per se, rather to assess its validity as an endurance parameter. As such, when participants were unable to maintain exercise at

CP the workload was reduced. As a result, the mean training intensity within the study corresponded to ~ 95 % of CP. So, despite the ease of measuring CP within athlete groups (that is, data can be collected in the field without any specialist equipment and more than one individual can be assessed at the same time), no studies appear to have examined the physiological or performance effects of training specifically *at* CP. This reflects a clear gap in the literature.

In order to speculate on the potential responses to training at CP, known adaptations to training at intensities equivalent to CP may be examined. For example, an analysis of previous literature reveals that CP corresponds to ~ 62 – 85 % of P-$\dot{V}O_{2max}$, or 113 – 175 % of P-LT (Baron *et al.*, 2005; Brickley *et al.*, 2002; Carter *et al.*, 2005; Dekerle *et al.*, 2003; McLellan & Cheung, 1992; Okudan & Gökbel, 2006; Overend *et al.*, 1992; Poole *et al.*, 1990; Pringle & Jones, 2002). The training adaptations associated with continuous exercise within this range of sub-maximal intensities includes the central and peripheral changes described in the previous section. Specifically, increases in both LT and $\dot{V}O_{2max}$ may be expected, as have been shown by Poole and Gaesser (1985) following eight weeks of training three times per week for 35 min at ~ 70 % of $\dot{V}O_{2max}$. In addition, improvements in exercise economy (i.e., the oxygen uptake required at a given absolute exercise intensity) may be expected following sub-maximal training, as the $\dot{V}O_2$ for a set work load is lower in trained versus untrained endurance athletes (Morgan *et al.*, 1995). However, it appears that improvements in exercise economy may require long-term exposure to endurance training rather than acute interventions lasting 6 – 12 weeks (Bangsbo & Larsen, 2000; Jones & Carter, 2000).

Local muscle responses to training around CP may also be considered by examining the existing findings from sub-maximal training intervention studies. Since the mitochondria are the main sub-cellular structures determining the aerobic capacity and fatigue resistance to prolonged contractile activity in skeletal muscle, a fundamental principle of endurance training is to increase mitochondrial enzyme activity (Coffey & Hawley, 2007). Work with humans has shown cycle training at exercise intensities comparable to CP (i.e., 60 – 90 % of $\dot{V}O_{2max}$) to elicit significant increases in the mitochondrial enzyme activities of citrate synthase (CS) and succinate

dehydrogenase (SDH). These findings are summarised in table 4.2. Although two studies showed no significant increases in CS or SDH following 2 h of exercise at 60 – 67 % of $\dot{V}O_{2max}$ over 5 – 12 consecutive days (Green *et al.*, 1992; Putman *et al.*, 1998), these results are opposed by Chesley *et al.* (1996) and Spina *et al.* (1996) using similar training protocols. Spina *et al.* (1996) argue that mitochondrial enzyme adaptive responses to exercise begin almost immediately after initiation of the adaptive stimulus, with CS activity increasing alongside other metabolic changes such as a smaller decrease in high-energy phosphates, smaller increases in inorganic phosphate ($P_i$), creatine and ADP, slower glycogen depletion and lower $La^-$ production. While the short-term training effects on CS and SDH continue to be contended, longer duration training interventions (lasting $\geq$ 9 weeks) that involve 4 – 6 sessions per week at intensities of at least 65 % of $\dot{V}O_{2max}$ lead to clear increases in aerobic enzyme activity (Dubouchaud *et al.*, 2000; Gollnick *et al.*, 1973).

Table 4.2: A summary of the effects of cycle ergometer training on citrate synthase (CS) and succinate dehydrogenase (SDH) activities (listed in order of intervention duration)

| Author, date | Training protocol | Enzyme | Training effect |
|---|---|---|---|
| Green *et al.* (1992) | 120 min at 67% $\dot{V}O_{2max}$<br>Consecutive days for 5 – 7 days | CS<br>SDH | NSD in activity<br>NSD in activity |
| Chesley *et al.* (1996) | 120 min at 65% $\dot{V}O_{2max}$<br>Consecutive days for 6 days | CS | 20% increase |
| Putman *et al.* (1998) | 120 min at 60% $\dot{V}O_{2max}$<br>Consecutive days for 7 – 8 days | CS | NSD in activity |
| Spina *et al.* (1996) | 120 min at 60 – 70% $\dot{V}O_{2max}$<br>Consecutive days for 7 or 10 days | CS | 30-35% increase |
| Dubouchaud *et al.* (2000) | 60 min at 75% $\dot{V}O_{2max}$<br>(intervals in last 2 weeks)<br>6 x per week for 9 weeks | CS | 75% increase |
| Gollnick *et al.* (1973) | 60 min at 65 – 90% $\dot{V}O_{2max}$<br>4 x per week for 5 months | SDH | 95% increase |

NSD: no significant difference

The current section may be concluded by acknowledging the gap that exists in the training literature regarding physiological responses to training at CP. Based on the studies that have shown responses to training at ~ 60 – 90 % of $\dot{V}O_{2max}$, it may be hypothesised that repeated exposure to continuous bouts of exercise at CP would lead to significant increases in LT, CP, $\dot{V}O_{2max}$, CS, SDH and, perhaps, economy.

**4.4) Summary**

This review of literature has illustrated an abundance of research that has investigated the methods for modelling CP. Furthermore, the potential influences of varying the number of trials, recovery between trials, trial durations and trial intensities when performing TTE tests for deriving CP estimates have been outlined. A considerable amount of research has focused on the physiological responses to exercise at (and slightly above) CP, although conclusions have been conflicting and the inconsistencies do not appear to be explained by differences in modelling methods or population group characteristics. Finally, little research has investigated the application of CP to exercise performance across population groups or to training. It is the focus of this thesis, therefore, to consider the potential applications of CP to endurance exercise.

# 5) Experimental Plans and General Methods

## 5.1) Rationale for the study

The three previous chapters have served to provide an in-depth review of the literature relating to the CP construct and the areas that have lacked research attention to date. Two of these areas have been specifically chosen as the focus for the following studies: (i) the application of CP across a range of participant populations categorised according to aerobic fitness, and (ii) the application of CP in training. Cycle ergometry will be employed as the exclusive mode of exercise throughout the studies, in an effort to generate data that may be compared with previous research literature. In addition, cycle ergometry provides a practical method for deriving CP, for comparing groups of different fitness levels and for training groups of individuals within a laboratory setting.

## 5.2) Significance of the study

The health benefits of exercise are widely documented and regular physical activity is recommended to improve lifestyle and reduce the risk of numerous diseases (Hardman & Stensel, 2003). Providing inactive populations with a method to easily determine a personal exercise intensity that optimises exercise tolerance would be highly desirable. In addition, an easy-to-administer exercise protocol that impacts upon high-level athletic performance would be attractive to coaches and athletes.

## 5.3) Research aims

The main research aims of the following studies will be:
(i) to investigate the physiological characteristics of CP and the physiological responses to exercising at and around CP across groups with different levels of aerobic fitness;
(ii) to compare the effects of continuous and intermittent training on CP;
(iii) to ascertain whether CP may be used as an effective training intensity for improving aerobic fitness.

**5.4) Participants**

All prospective participants received a detailed information pack relating to the experiment with the associated benefits and risks clearly stated (*Appendix A*). Provided participants were satisfied with the protocol and testing commitments they completed a health and activity questionnaire and, if fulfilling all requirements for involvement in the experiment, completed and signed a consent form prior to initial laboratory testing (*Appendix B*). Participants also completed the Baecke *et al.* (1982) Habitual Physical Activity Questionnaire, or H-PAQ (*Appendix C*). The right to withdraw from the study at any time was made clear to all prospective participants. All experimental procedures were approved by the University's Ethics Committee.

**5.5) Laboratory**

All experimental work was carried out in the BASES accredited exercise physiology laboratory within the Chelsea School, University of Brighton. The laboratory temperature was set to 19$^o$C for all exercise tests and training sessions. A fan was used on request for further cooling. On the initial laboratory visit height was measured to within 0.1 cm using a Harpenden stadiometer and body mass was measured to within 0.1 kg.

**5.6) Cycle ergometry**

*5.6.1) Cycle ergometers*

Three different types of cycle ergometer were used to complete the work within this thesis. The reliability of TTE (chapter 6) and the pre- and post-training characteristics (chapter 9) were examined using an electrically-braked SRM cycle ergometer with strain gauges at the crank for accurate torque measurement (SRM, Julick, Germany). The SRM system records second-by-second power output and before each test the SRM powermeters were calibrated according to the manufacturer's recommended procedure (Jones & Passfield, 1998). The study comparing fitness groups (chapter 7) used an electrically-braked Lode cycle ergometer (Lode Corival, Groningen, The Netherlands). No power output data was stored using this system. Finally, all

training was performed on friction-braked cycle ergometers (Monark Ergomedic 620, Varberg, Sweden). Again, power output was not recorded. The seat, handlebar and crank length positions were measured for all cycle ergometers and remained constant throughout all tests for each individual.

*5.6.2) Self-selected cadence*

During the warm-up of initial tests or familiarisation sessions for all studies, participants were instructed to choose a SSC at which all subsequent cycle ergometer tests would be completed. Untrained individuals and non-cyclists were guided to select a cadence close to $70 - 80$ rev·min$^{-1}$ (Takaishi *et al.*, 1994). Trained cyclists were given no specific guidelines, but were instructed to select a cadence that would be comfortable over a full range of exercise intensities (i.e., from very light to maximal). A SSC was imposed during all experimental tests since it appears to delay fatigue, regardless of training status (Takaishi *et al.*, 1994; Takaishi *et al.*, 1996), and it has shown higher TTE values to be obtained compared with cycling at SCC $\pm$ 10% (Weissland *et al.*, 1997).

**5.7) The lactate threshold test**

*5.7.1) Identifying the lactate threshold*

Resting $[La^-]_{bl}$ was measured prior to exercise and a 10-min warm-up was completed at 50, 75 or 100 W depending on the body mass of the individual and physical activity information provided in individual questionnaires. The final 3-min period of the 10-min warm-up was treated as the first stage of the LT test and stages increased by 25 W every 3 min thereafter. During the final minute of each 3-min stage a fingertip blood sample was collected and a rating of perceived exertion (RPE) was recorded. Signs of attaining LT during the test included an RPE > 13 (Okura & Tanaka, 2001) and a HR value approximately equal to $80 - 85$ % of the maximal HR predicted for age (i.e., 220 minus age). On reaching one of these criteria, participants completed one or two more 3-min stages to ensure that LT had been exceeded but that maximal exertion was not attained.

The P-LT was determined from the relationship between power output and $[La^-]_{bl}$ and was visually identified as the point at which the rate of $[La^-]_{bl}$ production and diffusion exceeded the rate of removal (i.e., the LT defined in chapter 3 as a sudden and sustained increase in the gradient of the work rate-$[La^-]_{bl}$ curve). Examples of individual LT identification are displayed in figures 7.1 and 9.3. Where expired air was collected in the final minute of each 3-min stage, $\dot{V}O_2$ at LT ($\dot{V}O_2$-LT) was derived from the linear relationship between power output and $\dot{V}O_2$.

*5.7.2) Blood lactate measurement*

Fingertip blood samples were analysed for $[La^-]_{bl}$ using an automated analyser (YSI 2300, Yellow Springs, Ohio, USA). The analyser was calibrated prior to analysis of the first blood sample during each testing session and was automatically re-calibrated after every four blood samples. Prior to sampling the fingertip was swabbed with alcohol to clean the site (Alcowipe, Seton Healthcare Group plc, Oldham, England). A sterile safety lancet (HemoCue AB, Ängelholm, Sweden) was then used to puncture the skin of the fingertip. The first drop of blood was wiped away with a tissue before the capillary blood samples (~ 25 µL) were collected in capillary tubes containing the anticoagulant ethylenediaminetetraacetic acid, or EDTA (Microvette® CB 300, Sarstedt, Nümbrecht, Germany).

**5.8) The incremental ramp test**

Following the LT test an incremental ramp test to exhaustion (RAMP) commenced at a power output approximately equal to P-LT, such that exhaustion would ensue within 8 – 10 min. Performing an LT test prior to a RAMP has been shown to elicit similar $\dot{V}O_{2max}$ values compared to those elicited when the RAMP is not preceded by an LT test (Jones & Doust, 1996). Increases in power output were automatically imposed by the cycle ergometer at a rate of 5 W every 15 s (i.e., 20 W·min$^{-1}$). Strong verbal encouragement was provided, particularly towards the latter stages of the test, and the test was terminated at the point of volitional exhaustion or when pedalling frequency dropped by > 10 rev·min$^{-1}$ below the SSC following a warning. The RPE was recorded during the final 15 s of each stage and at the end of the test.

*5.8.1) Maximal minute power*

The maximal power output attained during the RAMP was calculated as the maximal minute power (MMP) as follows:

$$MMP \text{ (W)} = [EP \times (t_1/60)] + [(EP - 20) \times (t_2/60)] \quad \textit{equation 6}$$

where EP represents the end power output (the power output attained at the end of the test), $t_1$ represents the time (in seconds) spent at EP, and $t_2$ is equal to $(60 - t_1)$.

*5.8.2) Gas exchange: Douglas bag method*

The Douglas bag method of collecting expired air was used in the reliability study (chapter 6), throughout the study comparing fitness groups (chapter 7) and during the training sessions in the training study (chapter 9). Prior to testing, participants were familiarised with breathing through a low-resistance Hans Rudolph respiratory valve system while wearing a rubber nose-clip. During experimental trials, expired air samples were collected for ~ 1 min per sample with the air passing through a 1-metre length of Falconia tubing and into a 200-L Douglas bag. Air was analysed for oxygen ($O_2$) and carbon dioxide ($CO_2$) concentrations by 1-min sampling through a gas purity analyser (Servomex 4100, Crowborough, England), which was calibrated before each test using BOC certified gases of known concentration. The Douglas bags were subsequently evacuated using a Harvard dry gas meter to determine expiratory volume. Gas temperature was measured via a temperature probe within the volume meter. The concentration, volume and temperature measurements were combined with collection time and ambient pressure values to calculate respiratory gas exchange variables ( $\dot{V}O_2$ , $\dot{V}CO_2$ , $\dot{V}_E$ and the respiratory exchange ratio, RER), standardised to temperature, barometric pressure at sea level and dry gas (STPD). An example calculation of the respiratory gas exchange variables is presented in *Appendix D*.

*5.8.3) Gas exchange: breath-by-breath method*

The breath-by-breath expired air sampling method was used in the validity study (section 9.2) and during the pre- and post-training testing within the training study (chapter 9). Pulmonary gas exchange was determined breath-by-breath using an

Ergocard® system (Medisoft, Sorinnes, Belgium) with gas wave-forms aligned to the volume excursions at the mouth using a real time breath-by-breath alignment. Participants were connected to a bi-directional flow sensor via a low dead space (~ 90 mL), Hans Rudolph mouth-piece and saliva trap. Expired air was passed to the gas analysers using a moisture exchanger sampling line (Perma Pure LLC, New Jersey, USA), equating the sample to the ambient humidity. The gases were then corrected to STPD using algorithms similar to those reported by Beaver $et\ al.$ (1973). Gas analysis within the system used an infrared fast-response single beam for $CO_2$ and a paramagnetic fast-response differential analyser for $O_2$. The volume and concentration signals were integrated by computer following analogue-to-digital conversion and respiratory gas exchange variables ($\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$) were displayed for each breath and were subsequently cleaned and interpolated to provide 1-s values.

### 5.8.4) Maximal oxygen uptake

The attainment of $\dot{V}O_{2max}$ has been defined as the concomitant incidence of three of the following criteria: (i) a change in $\dot{V}O_2$ of $< 2.0$ mL·kg$^{-1}$·min$^{-1}$ from one stage to the next (i.e., a plateau), (ii) an RER value $> 1.1$, (iii) a HR value of $\geq 90$ % of the age-predicted maximum and/or (iv) a peak $[La^-]_{bl}$ of $\geq 8.0$ mmol·L$^{-1}$ (Howley $et\ al.$, 1995). However, it is not unusual for a plateau in $\dot{V}O_2$ to be absent at the end of maximal exercise testing and the secondary criteria listed here are not necessarily valid indicators of maximal effort (Day $et\ al.$, 2003; Midgley $et\ al.$, 2009; Midgley $et\ al.$, 2007; Poole $et\ al.$, 2008). Since the criteria were not always attained in the current experimental studies (for example, only 8 of the 25 participants in chapter 7 achieved three or four of the criteria; $Appendix\ E$), the term $\dot{V}O_{2peak}$ will be used throughout this thesis to reflect the highest $\dot{V}O_2$ measures obtained during a RAMP.

### 5.9) Heart rate measurement

Heart rate was monitored throughout each test and data was saved every 5 s using a telemetric HR monitor (Sports Tester, Polar Electro Oy, Kempele, Finland). The 5-s

data was downloaded for analysis using Polar Precision Performance software.  The highest HR value measured during the RAMP was defined as $HR_{peak}$.

## 5.10) Critical Power determination

### 5.10.1) Modelling Critical Power

Critical Power was determined using trials where P was fixed by the experimenter and TTE was measured.  Two alternatives to this 'fixed power' method of determining CP have been described as: (i) the 'fixed work' method, where total work done is fixed and TTE is measured, and (ii) the 'fixed time' method, where exercise time is fixed and total work done is measured (Hopkins *et al.*, 2001).  Fixed work and fixed time methods of measuring cycling performance may be better suited to trained athletes who are familiar with pacing strategies and who are more adept at achieving complete exhaustion within a set time period.  However, since a range of individuals (from non-cyclists to well-trained athletes) were targeted for participation in the current series of experiments, the fixed power method was chosen in an effort to overcome the potential bias of fixed work and fixed time models that may favour trained athletes.

### 5.10.2) Critical Power determination trials

The CP was determined by prescribing 3 – 5 TTE tests on separate days.  The intensities of the TTE tests (relative to MMP) differed between individuals and were selected to ensure exhaustion ensued within the required time interval of 3 – 15 min. Trials were preceded by a 5-min warm-up at 20 % of MMP, as this intensity was considered to be light for all participants.  Participants were unaware of exercise time throughout the duration of their CP determination trials (timing devices were covered) and no performance feedback (i.e., power output or HR data) was provided. Participants were instructed to maintain their SSC throughout the tests and to cycle for as long as possible.  Strong verbal encouragement was provided, particularly towards the latter stages of the TTE tests.  The tests were terminated when SSC decreased by $\geq 5$ rev·min$^{-1}$ following a first warning.

*5.10.3) Calculating Critical Power*

The P-t data points obtained during the TTE tests were used to model individual linear regression plots for CP determination.  Time (s) was inverted and plotted against P *(equation 3)* and the y-intercept defined CP.

*5.10.4) Calculating the $\dot{V}O_2$ at Critical Power*

The $\dot{V}O_2$ at CP was estimated ($\dot{V}O_2$-$CP_{est}$) using the P-$\dot{V}O_2$ relationship derived from the sub-maximal data obtained during the LT test.  The $\dot{V}O_2$-$CP_{est}$ as a % of $\Delta$ (i.e., the $\dot{V}O_2$ difference between LT and $\dot{V}O_{2peak}$, measured in mL·kg$^{-1}$·min$^{-1}$) was calculated using the following formula:

$$\dot{V}O_2\text{-}CP_{est}\ (\%\Delta) = 100 \times ([\dot{V}O_2\text{-}CP - \dot{V}O_2\text{-}LT]\ /\ [\dot{V}O_{2peak} - \dot{V}O_2\text{-}LT])\quad \textit{equation 7}$$

**5.11) Collaborative partnerships**

All data collection within this thesis was led and conducted by the chief researcher (i.e., the author of the thesis).  Additional help was provided during the training study (chapter 9) to enable full data collection within the strict time schedule and to enable muscle biopsies and analyses.  The research supervisory team contributed to the pre- and post-training data collection process for the LT and RAMP tests.  Non-training undergraduate students provided assistance (under author supervision) during the training sessions by modifying the resistance on the Monark ergometers and collecting HR and $\dot{V}O_2$ data.  A medical doctor performed the biopsies and the muscle samples were analysed in collaboration with the Department of Physiology, Anatomy and Genetics at the University of Oxford.

## 6) Reliability of Time to Exhaustion Testing

### 6.1) Introduction

The reproducibility of CP estimates that are derived from fixed power TTE trials was discussed in section 2.1.5. Repeated CP estimates were shown to be highly correlated (Gaesser & Wilson, 1988; Nebelsick-Gullett et al., 1988) but increased on a second determination (Bishop & Jenkins, 1995; Smith & Hill, 1993). Since CP is derived from individual TTE trials, logical reasoning would imply that the variation in CP estimates would be influenced by the reproducibility of the individual trials and this concept was introduced in section 2.2.3. Longer-duration tests (i.e., ~ 8 – 16 min) were reported to increase significantly from trial 1 to 2, and again from trial 2 to 3, while shorter- and medium-duration tests (i.e., < 5 min) did not differ over three trials (Bishop & Jenkins, 1995). Although the authors concluded that longer-duration TTE trials for CP determination were more sensitive to motivation and learning effects, no statistical measures of reliability were presented.

In a review article, Hopkins et al. (2001) have more recently reported CV values of 1.6 and 4.6 % for fixed work cycle tests lasting ~ 6 and 10 min, respectively. While these CV data support the idea that longer exhaustive trials are less reliable than shorter exhaustive trials, it should be noted that the values were derived from two different studies that used male cyclists and untrained males and females for the shorter and longer tests, respectively. This difference in training status is likely to have amplified the difference in CV, since trained individuals appear to produce less variable TTE data than untrained individuals (Hopkins et al., 2001). As such, it is possible that a more homogenous participant group would produce more similar CV values for short- and long-duration TTE tests.

The reliability of TTE tests for CP modelling has been investigated in a single study using competitive male runners performing running exercise, whereby CV values of 9 – 16 % were reported for trials lasting ~ 2 – 8 min (Hinckson & Hopkins, 2005). However, the reliability of short- and long-duration TTE trials typically used for CP determination does not appear to have been compared for fixed power tests in a single

study using cycling exercise. Moreover, previous reliability studies tend to have used only two repeated trials (Hopkins *et al.*, 2001), which limits the ability to examine changes in CV as participants become accustomed to the exercise task over time. Since repeated TTE trials may be associated with motivation and learning effects, it is important to identify the optimal number of familiarisation sessions that are required to maximise TTE reliability. Therefore, the purpose of the present study was to ascertain the variation in TTE for individuals not specifically trained in cycle-ergometer exercise over 10, repeated TTE trials lasting ~ 3 – 15 min. It was hypothesised that:

1. TTE would demonstrate improved reproducibility over the series of 10 trials;
2. the longer TTE trials would demonstrate greater variability than the shorter trials.

**6.2) Methods**

*6.2.1) Experimental overview*

Five males and three females who were familiar with an exercise laboratory environment but were not experienced in exhaustive cycle-ergometer exercise volunteered to participate in the present study. Mean ± standard deviation (SD) participant characteristics were: age, $26.2 \pm 2.5$ y; body mass, $73.7 \pm 7.4$ kg; $\dot{V}O_{2peak}$, $46.3 \pm 8.8$ mL·kg$^{-1}$·min$^{-1}$. The first laboratory visit involved the completion of a RAMP for the assessment of $\dot{V}O_{2peak}$ and MMP. Following the RAMP, individuals were pair-matched as closely as possible for MMP and were randomly assigned to either a short- or a long-duration exercise group, ensuring at least one female was present in each group. The short-duration group (SHORT) completed 10, constant-power cycling exercise tests at 115 % of MMP and the long-duration group (LONG) completed 10, constant-load cycling exercise tests at 81 % of MMP. These intensities were intended to induce exhaustion after approximately 3 – 5 and 13 – 15 min, respectively (i.e., at either end of the trial-duration range for CP determination). During the final (twelfth) visit to the laboratory participants completed a second RAMP, which was administered to detect a training effect of the 10 TTE trials. All tests were completed on an SRM cycle ergometer at a constant SSC (see section 5.6).

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*6.2.2) Incremental ramp test*

The main RAMP procedures are described in section 5.8. Since the present study did not include an LT test, the RAMP commenced with a 5-min warm-up at 80 W for all participants and increased by 20 W·min$^{-1}$ thereafter. The $\dot{V}O_2$ was measured using the Douglas bag method with air collection at the end of each incremental stage (see section 5.8.2) and HR was monitored throughout the test. Blood samples were collected 3 min after the end of the RAMP for the measurement of post-exercise [La$^-$]$_{bl}$ (see section 5.7.2).

*6.2.3) Time to exhaustion trials*

Individuals completed 10 TTE trials on separate days for the evaluation of test variability, each within one hour of the start time of the first test in order to eliminate any diurnal variation effects (Carter *et al.*, 2002). Participants were instructed to follow a similar diet prior to each test, to refrain from caffeine consumption on the day of testing and to refrain from alcohol consumption on the day of and the day prior to each test. Tests were separated at regular intervals for each participant by 1 – 7 days and individuals completed all 10 tests within 3 – 6 weeks. For logistical reasons, and since TTE testing of a similar intensity and duration (i.e., 90 % of $\dot{V}O_{2max}$ for ~ 12.5 min) has previously revealed no significant changes in endurance performance at different phases of the menstrual cycle (Lebrun *et al.*, 1995), no specific adjustments were made for the timing of tests for female participants.

On arrival at the laboratory a blood sample was collected for the analysis of resting [La$^-$]$_{bl}$ before the commencement of a 5-min warm-up at 20 % of MMP. Immediately following the 5-min warm-up, the cycle ergometer resistance was increased to the required workload of either 115 or 81 % of MMP. All timing devices were concealed from the participant and individuals were encouraged to cycle for as long as possible, with strong verbal encouragement provided during the latter stages of the test. The HR was monitored continuously throughout each test and peak HR was calculated as the highest HR value recorded during the trial. The test was terminated when cadence dropped by $\geq$ 5 rev·min$^{-1}$ on a second occasion after a warning, or when the

participant was unable to continue the exercise, and peak RPE was recorded immediately.  A final blood sample was collected 3 min after the end of the exercise for the analysis of post-exercise $[La^-]_{bl}$.

*6.2.4) Coefficient of variation*

The CV, defined by Schabort *et al.* (1998) as the within-subject variation expressed as a percent of the subject's mean, is based upon the change in mean performance over consecutive pairs of trials for individual participants and was calculated using the following formula:

$$CV = 100 \text{ x (SD / Mean)}$$
*equation 8*

The matrix of CV values for TTE was reduced to a summary of mean values for each pair of consecutive trials.  While any mean value would typically be derived by summing individual values and dividing by the total number of inputs, this method has been reported to produce a biased estimate of overall mean CV (Schabort *et al.*, 1998).  Therefore, adjusted estimates were obtained by taking the square root of the average of the square of the CV values of individual participants, as has been used previously (McGawley & Bishop, 2006).  An example of the calculations is provided in *Appendix F* using the formula:

$$\text{Adjusted mean CV} = \sqrt{(\Sigma(CV^2)/n)}$$
*equation 9*

where n represents the total number of participants.

*6.2.5) Data analyses*

Descriptive statistics are expressed as mean ± SD and tests of difference are reported as mean ± standard error of the mean (SEM).  The Statistical Package for the Social Sciences (SPSS) 14.0 was used to carry out statistical analyses and the level of significance was set at $P < 0.05$.  Between-group characteristics were compared using individual-samples t-tests and within-participant data were compared pre- and post-TTE trials using paired t-tests.  Changes in performance and physiological variables over the 10 trials, and CV values over the nine pairs of consecutive trials, were assessed using a one-way analysis of variance (ANOVA) with repeated measures. Sphericity was checked using Mauchly's test and the Greenhouse-Geisser correction

was used in all cases (epsilon < 0.75).  Non-parametric correlations were analysed using Spearman's rho tests.

## 6.3) Results

### 6.3.1) Descriptive data

Participant characteristics recorded prior to completion of the 10 TTE trials are outlined in table 6.1.  Age, body mass, $\dot{V}O_{2peak}$ and MMP were not different between groups (P > 0.05) and there were no significant changes in body mass (P = 0.054), $\dot{V}O_{2peak}$ (P = 0.771) or MMP (P = 0.444) from pre- to post-TTE testing.  The workloads prescribed for the 10 TTE tests were 299 ± 57 W and 228 ± 59 W for the SHORT and LONG groups, respectively, and within-participant measured power output did not differ over any of the 10 trials (P > 0.05).

Table 6.1: Individual and group characteristics prior to time-to-exhaustion testing

| Group | Participant | Age (y) | Body Mass (kg) | $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$) | MMP (W) |
|---|---|---|---|---|---|
| SHORT | 1 (F) | 28 | 68.4 | 34.4 | 198 |
| | 2 | 28 | 72.6 | 50.1 | 283 |
| | 3 | 23 | 73.2 | 57.7 | 313 |
| | 4 | 22 | 77.7 | 42.0 | 247 |
| | *Mean ± SD* | *25 ± 3* | *73.0 ± 3.8* | *46.0 ± 10.0* | *260 ± 50* |
| LONG | 5 (F) | 30 | 62.9 | 45.8 | 229 |
| | 6 (F) | 27 | 68.1 | 42.4 | 231 |
| | 7 | 25 | 83.8 | 39.1 | 281 |
| | 8 | 27 | 82.8 | 59.3 | 384 |
| | *Mean ± SD* | *27 ± 2* | *74.4 ± 10.5* | *46.7 ± 8.9* | *281 ± 73* |

MMP: maximal minute power; F: female; no significant differences between groups (P > 0.05)

### 6.3.2) Reliability of time to exhaustion

The mean ± SEM TTE data are illustrated in figures 6.1*a* and 6.1*b*.  The TTE for the SHORT group (for all 40 trials) was 152 ± 8 s, with the shortest and longest trials (i.e., trials 3 and 8) lasting 144 ± 22 s and 166 ± 36 s, respectively.  Individual TTE

durations ranged from 106 – 271 s. The TTE for the LONG group (for all 40 trials) was 555 ± 44 s, with the shortest and longest trials (i.e., trials 9 and 5) lasting 439 ± 117 s and 617 ± 155 s, respectively. Individual TTE durations ranged from 206 – 1268 s. There were no significant differences in TTE over any of the trials for either of the two groups (P > 0.05). The adjusted mean CV values for TTE over each pair of trials are displayed in table 6.2. Statistical analyses were carried out on the raw CV data to compare pairs of consecutive trials and no significant differences were found for either the SHORT or the LONG groups (P > 0.05).
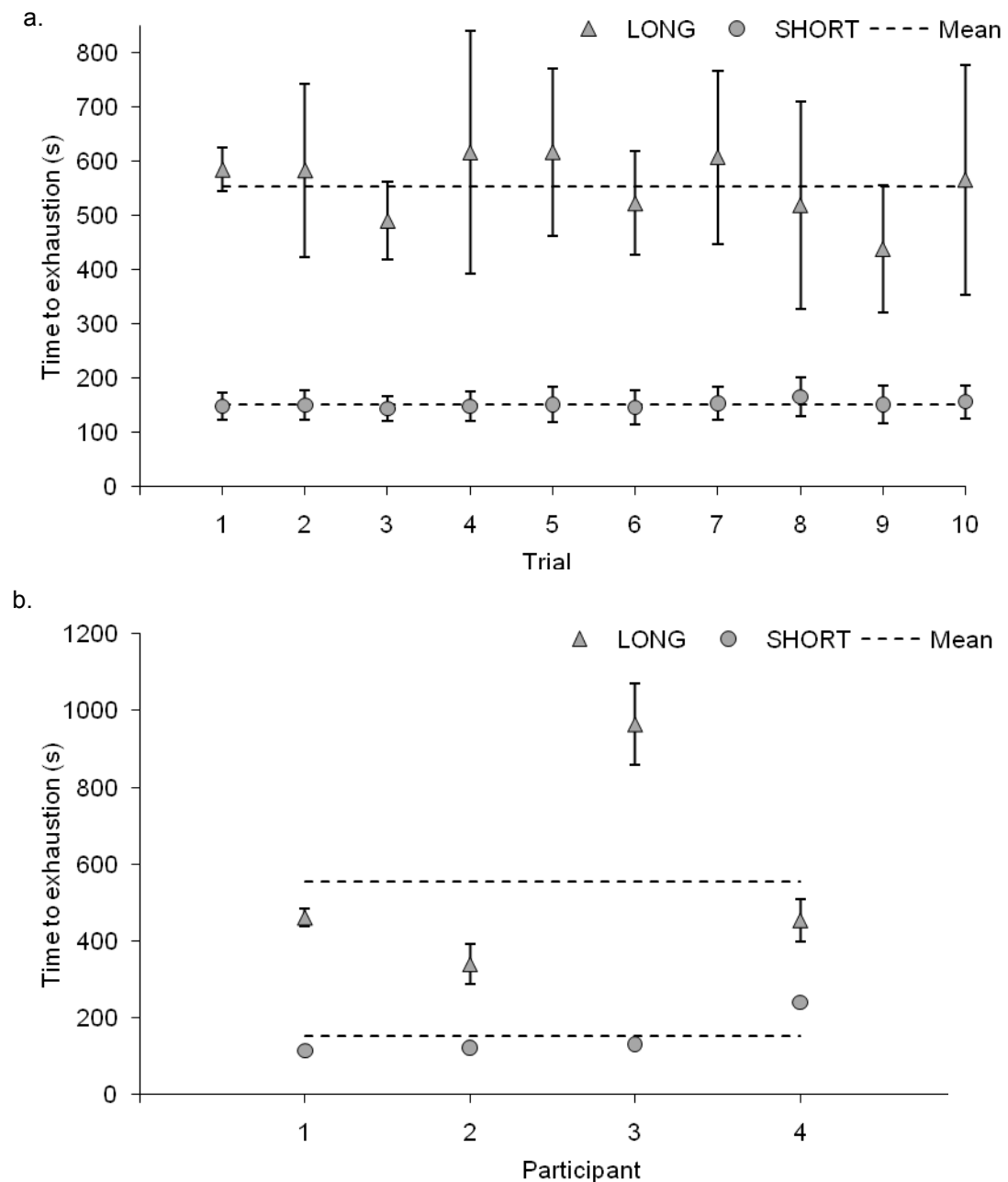


Figure 6.1: Mean ± SEM time to exhaustion over the 10 trials for a.) the SHORT and LONG groups, and b.) individual participants

Table 6.2: Adjusted mean coefficient of variation values (%) for time to exhaustion over pairs of consecutive trials for the SHORT and LONG groups

| Consecutive Trials | 1-2 | 2-3 | 3-4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 9-10 |
|---|---|---|---|---|---|---|---|---|---|
| SHORT | 3.5 | 4.5 | 4.4 | 4.7 | 3.5 | 5.6 | 7.6 | 10.5 | 4.8 |
| LONG | 22.8 | 16.5 | 25.6 | 14.3 | 12.1 | 13.8 | 31.7 | 24.9 | 19.8 |

*6.3.3) Physiological responses during the time to exhaustion trials*

The mean ± SEM peak HR (as a % of $HR_{peak}$) and post-exercise $[La^-]_{bl}$ (expressed in $mmol \cdot L^{-1}$) attained during each of the 10 trials are displayed in figures 6.2 and 6.3, respectively. There were no significant differences for either variable over the 10 trials for either group (P > 0.05). Peak RPE ranged from 17 to 20 for both groups and no significant differences were identified between trials for either group (P > 0.05).
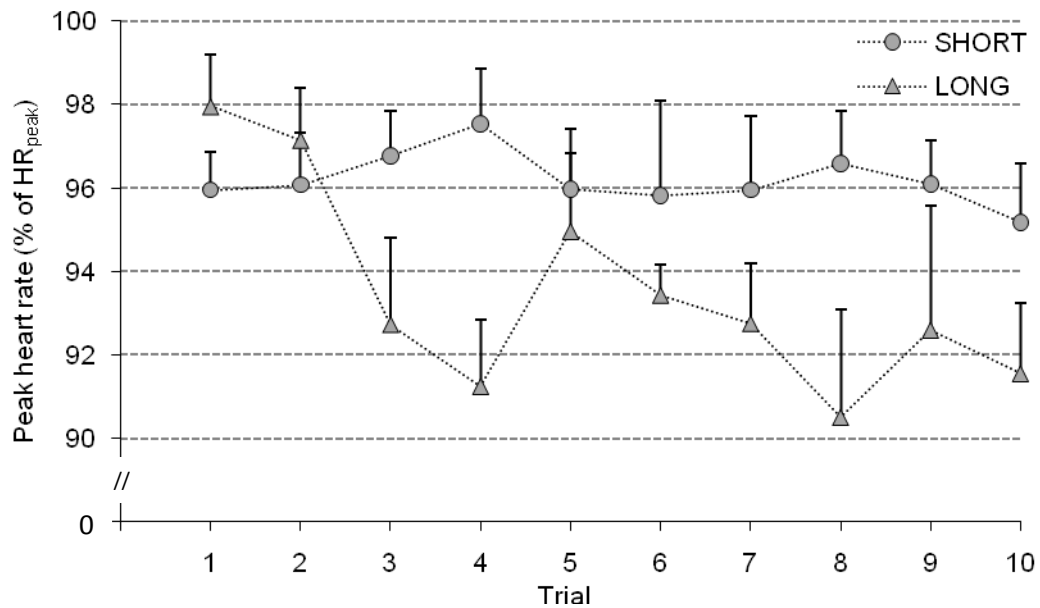


Figure 6.2: Mean ± SEM peak heart rate as a % of $HR_{peak}$ for the SHORT and LONG groups
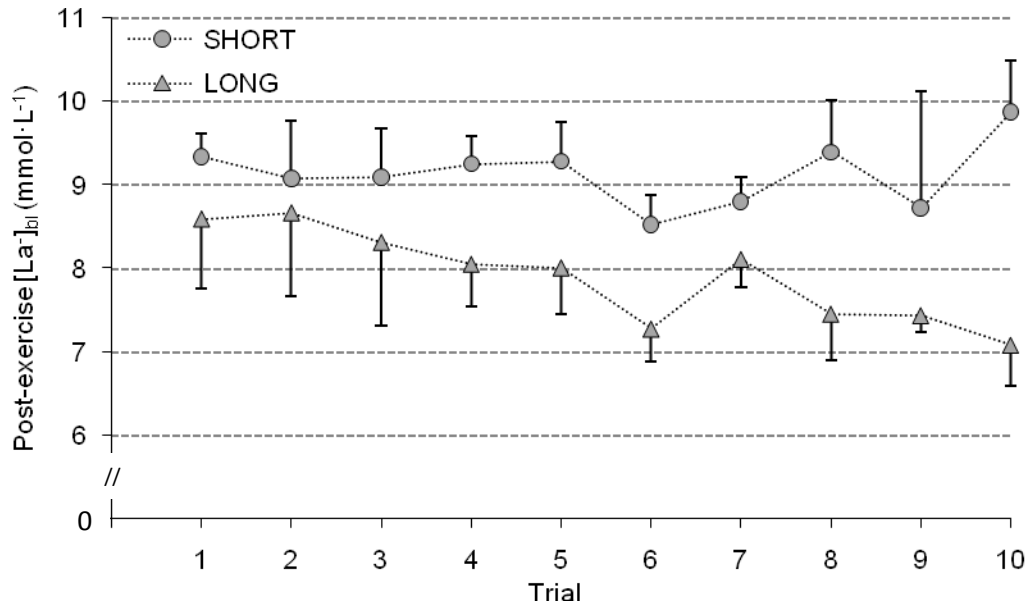
Figure 6.3: Mean ± SEM post-exercise blood lactate concentration ($[La^-]_{bl}$) in mmol·L$^{-1}$ for the SHORT and LONG groups

*6.3.4) The attainment of a maximal physiological effort*

Despite no significant differences in TTE over the 10 trials, the CV data show that consecutive trials were highly variable, particularly for the LONG group. This implies that a maximal physiological effort may not have been exerted by individuals during every trial. To examine this possibility, relationships between relative TTE (i.e., as a % of an individual's longest TTE duration) and both relative peak HR (as a % of $HR_{peak}$) and relative post-exercise $[La^-]_{bl}$ (as a % of the highest $[La^-]_{bl}$ value measured during the 10 trials) were investigated. The SHORT and LONG group data were separated for statistical and illustrative purposes and results are displayed in figures 6.4 and 6.5 for HR and $[La^-]_{bl}$, respectively. Although no significant correlations were identified between TTE and either relative peak HR or relative $[La^-]_{bl}$ for the SHORT group ($r < 0.24$, $P > 0.05$), TTE was significantly correlated with relative peak HR ($r = 0.35$, $P = 0.028$; figure 6.4) and relative post-exercise $[La^-]_{bl}$ ($r = 0.49$, $P = 0.001$; figure 6.5) for the LONG group. While relationships were also explored for TTE (as a % of the longest TTE duration) versus (i) post-exercise $[La^-]_{bl}$ measured in mmol·L$^{-1}$, (ii) post-exercise $[La^-]_{bl}$ expressed as a % of peak $[La^-]_{bl}$ measured after the RAMP and (iii) peak HR as a % of the highest HR value measured during the 10 trials, no significant correlations were identified for either group ($r < 0.28$, $P > 0.05$).

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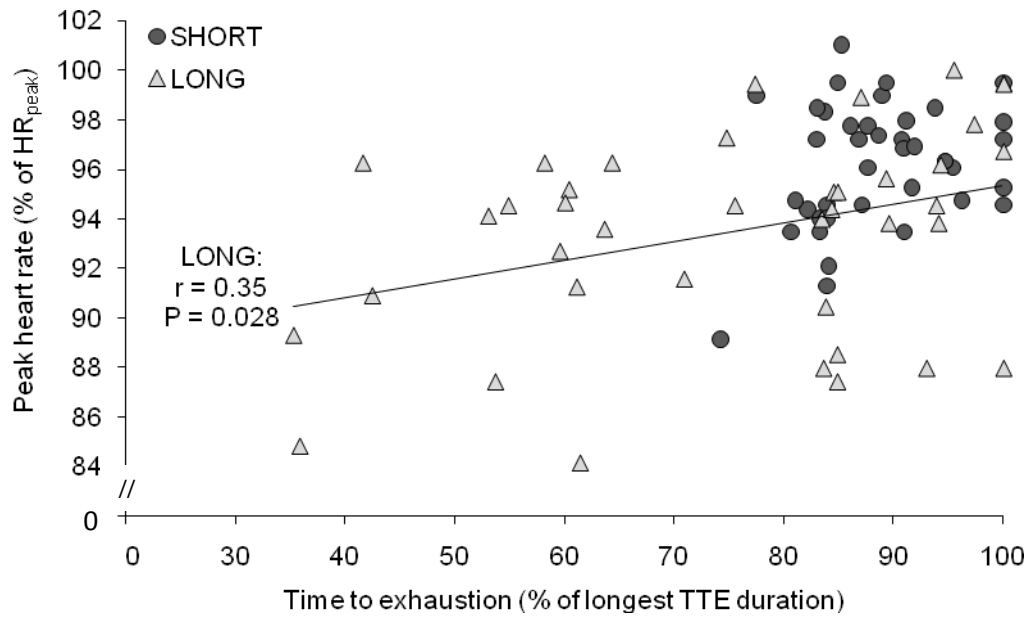
Figure 6.4: Time to exhaustion as a % of the longest TTE duration versus peak heart rate as a % of $HR_{peak}$ for the SHORT and LONG groups
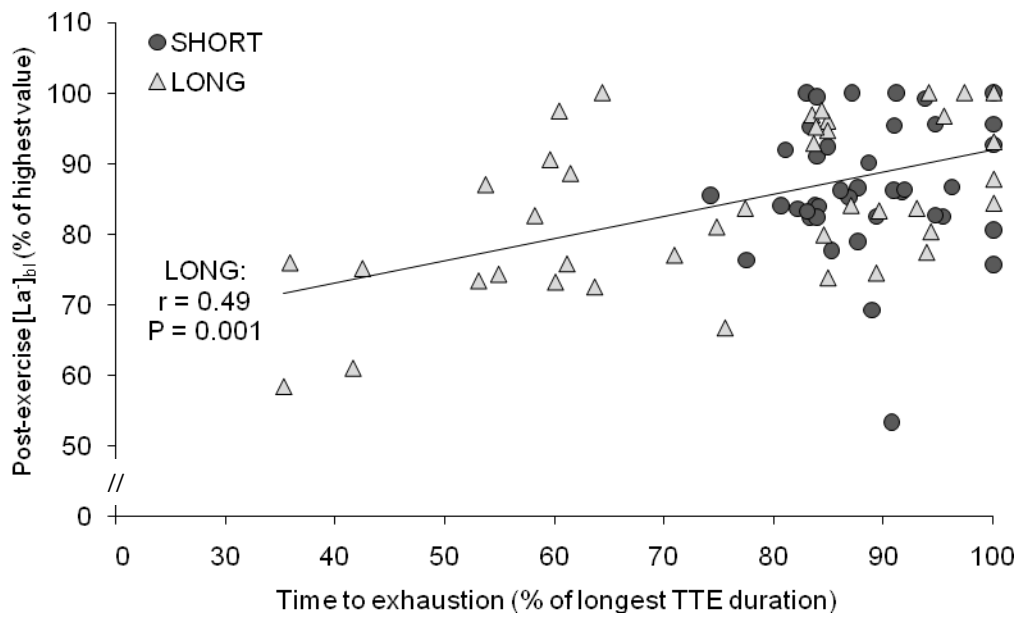


Figure 6.5: Time to exhaustion as a % of the longest TTE duration versus post-exercise blood lactate concentration ($[La^-]_{bl}$) as a % of the highest peak value for the SHORT and LONG groups

**6.4) Discussion**

*6.4.1) Reliability of time to exhaustion*

The present study has shown that the TTE values elicited for constant-load exercise were not statistically different over 10 repeated cycling trials at either 115 or 81 % of MMP. Furthermore, the CV for TTE was not significantly different for any consecutive pairs of trials at either intensity. These findings fail to support the first hypothesis stated in section 6.1 and suggest that familiarisation or learning effects are not inherent to exhaustive, constant-load exercise lasting ~ 3 – 15 min. Since this range of exercise durations was intended to reflect the range of durations used for CP determination, it may be implied that familiarisation sessions would not be effective in improving the reliability of TTE data for P-t$^{-1}$ modelling.

Findings from the present study are comparable to those previously reported for TTE over consecutive trials of short duration. For example, the average TTE for the SHORT group in the present study (152 ± 8 s) was between the short- and medium-durations (of 53 ± 3 and 277 ± 39 s, respectively) presented by Bishop and Jenkins (1995). These authors also reported no change in TTE over consecutive trials (i.e., from trial 1 to 2, or from trial 2 to 3). By contrast, however, Bishop and Jenkins (1995) showed that TTE increased significantly from trial 1 to 2 and again from trial 2 to 3 during tests lasting between 508 ± 48 and 965 ± 155 s, which are similar to the mean durations of 439 – 617 s recorded for the LONG group in the current study (which did not increase from trial to trial). This discrepancy may be due to the magnitude of intra-individual differences within the present study for TTE in the LONG group and suggests that longer-duration TTE trials are not uniformly sensitive to learning effects.

The CV values reported in the present study for the SHORT and LONG groups (3.5 – 10.5 % and 12.1 – 31.7 %, respectively) are considerably higher than those reported previously (i.e., 1.6 and 4.6 %) for exhaustive trials lasting ~ 6 and 10 min (Hopkins *et al.*, 2001). This may be due to the values reported by Hopkins *et al.* (2001) originating from 5-km cycle-ergometer time-trial data (i.e., fixed work tests), which

have been reported to produce less variation than fixed power tests (Jeukendrup *et al.*, 1996). The only study to have reported CV values for exhaustive, fixed power cycle ergometer tests using an exercise intensity and durations reflective of CP determination trials (i.e., 80 % of $\dot{V}O_{2max}$ and 14.1 – 18.2 min, respectively) reported individual CV values of 2.8 – 31.4 % (McLellan *et al.*, 1995). The upper end of this range is similar to the highest adjusted mean CV value calculated for the LONG group within the present study (i.e., 31.7 %). Since McLellan *et al.* (1995) found no significant differences between TTE over their five repeated trials, they concluded that large CV values prevented any familiarisation effect within their group of untrained participants and supposed that CV would decrease with further trials. However, this explanation is not supported by the current results, which showed no further decrease in CV in the LONG group over a second set of five TTE trials. As such, familiarisation does not appear to occur when performing more longer-duration TTE tests.

The high CV values reported for the LONG group in the present study reflect poor reliability over the series of 10 trials and support the second hypothesis (i.e., that the longer TTE trials would demonstrate greater variability than the shorter trials). The greater intra-individual variability in TTE for the LONG group compared with the SHORT group is demonstrated by a maximum difference of 132 – 587 s for participants in the LONG group, whereas participants in the SHORT group experienced maximum differences in TTE of only 23 – 61 s over the 10 trials. This variation reflects increases of 34 – 183 % from an individual's shortest to longest trial in the LONG group, and only 22 – 35 % in the SHORT group. Such large intra-individual variation, with almost three-fold increases in TTE from the shortest to the longest trial for two of the four LONG group participants, was unexpected and explains the large adjusted mean CV values in table 6.2.

*6.4.2) Physiological responses*

Although results showed that HR and [La⁻]$_{bl}$ did not differ over the 10 trials, the significant correlations between relative TTE and both peak HR and post-exercise [La⁻]$_{bl}$ for the LONG group (r ≥ 0.35, P < 0.05) provide some evidence to suggest that

below-maximal exhaustive efforts were characterised by less severe physiological responses. A significant relationship was not observed for the SHORT group, perhaps due to the smaller range of relative TTE data, whereby all trials lasted > 70 % of the longest TTE duration. These findings suggest that the reliability of longer-duration TTE data could be improved by imposing minimum criteria levels for relative HR and $[La^-]_{bl}$ responses. However, this possibility was not considered in the present study and further research is required to test this hypothesis.

## 6.4.3) Implications of the data

An important practical issue associated with the reliability of TTE trials is the impact of unreliable data on subsequent CP estimates. This can be examined using the mean ± SD TTE data reported in the current study and the associated mean power output values. For example, TTE was 152 ± 53 s at 299 W (i.e., for the SHORT group) and 555 ± 276 s at 228 W (i.e., for the LONG group). Using the mean $P-t^{-1}$ co-ordinates, a CP estimate of 203 W is produced (figure 6.6*a*). The effects on this CP estimate when one TTE data point lies 1 SD from the mean are illustrated in figures 6.6*b* and 6.6*c*. Figure 6.6*d* combines all five possibilities and shows that underperformance during the long-duration trial (i.e., Mean TTE - SD at 228 W) has the biggest effect on the CP estimate (148 W, compared with the original estimate of 203 W). A difference of 55 W for a CP estimate is the result of one data point deviating from the mean by 1 SD, which would be unacceptable in practice where accurate values are required. Figure 6.7 demonstrates the reduction in potential error of the CP estimate when three and four data points are used within the CP model. Since mean ± SD TTE data were not collected at power outputs between 81 % and 115 % of MMP in the present study, the $P-t^{-1}$ values for the additional co-ordinates were calculated to lie between the existing data at equidistant intervals. The additional power output used in figures 6.7*a* and 6.7*b* was 262 W and the mean ± SD TTE was 239 ± 101 s. In figures 6.7*c* and 6.7*d* the additional data points were at 273 W and 200 ± 80 s, and 250 W and 292 ± 130 s. The CP estimate using the mean TTE data remained at 203 W, since all $P-t^{-1}$ co-ordinates were equidistant. As more data points were used, with one data point always lying 1 SD from the mean, it is clear that the least accurate CP estimate moves closer to the original CP estimate of 203 W (166 and 177 W for the "worst" CP estimates using three and four $P-t^{-1}$ data points, respectively).
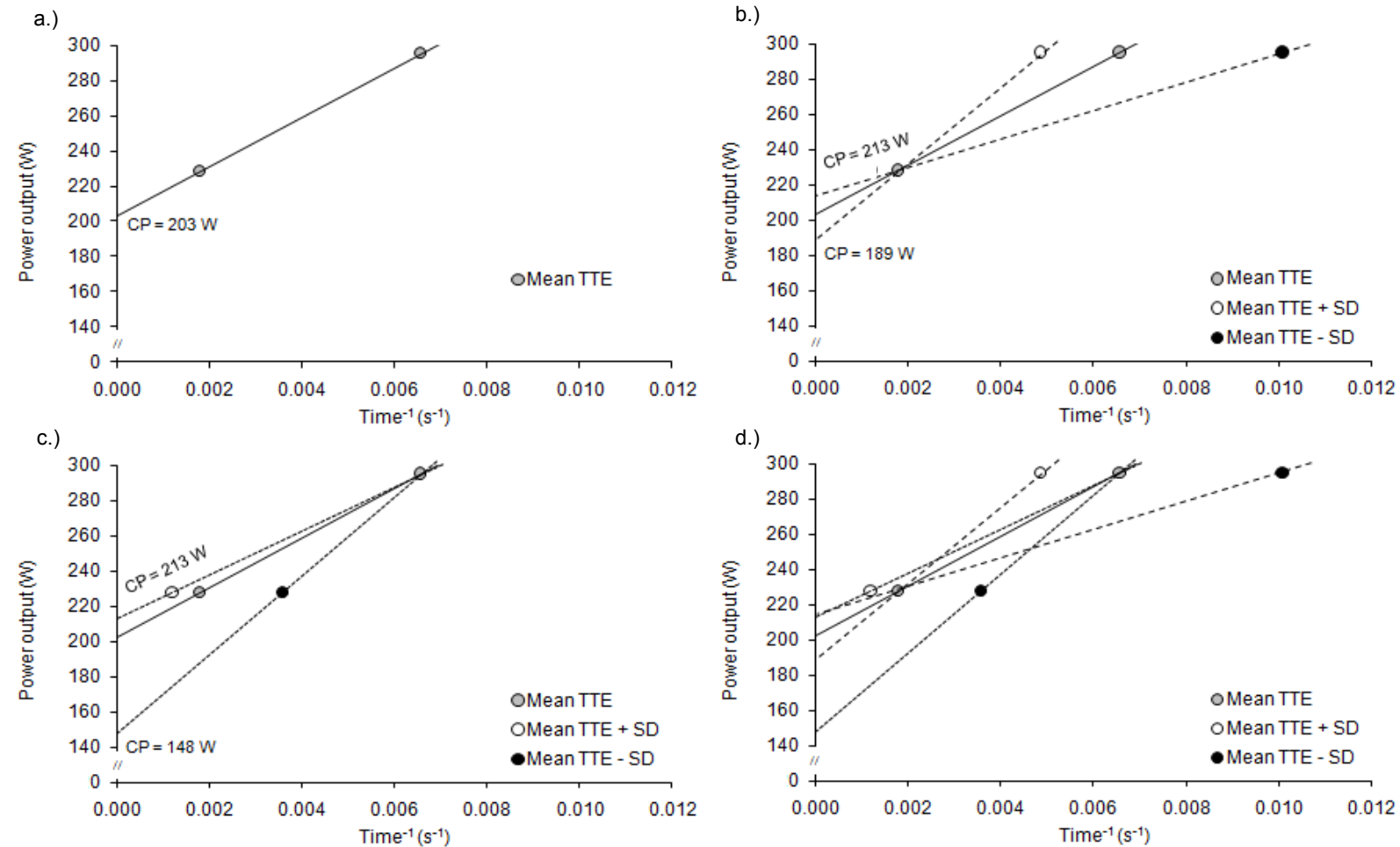
Figure 6.6: Different Critical Power estimates for a.) mean time to exhaustion data, b.) mean time to exhaustion data for the long-duration data point and the short-duration data point ± 1 SD, c.) mean time to exhaustion data for the short-duration data point and the long-duration data point ± 1 SD, and d.) all models described in figures 6.6a, 6.6b and 6.6c
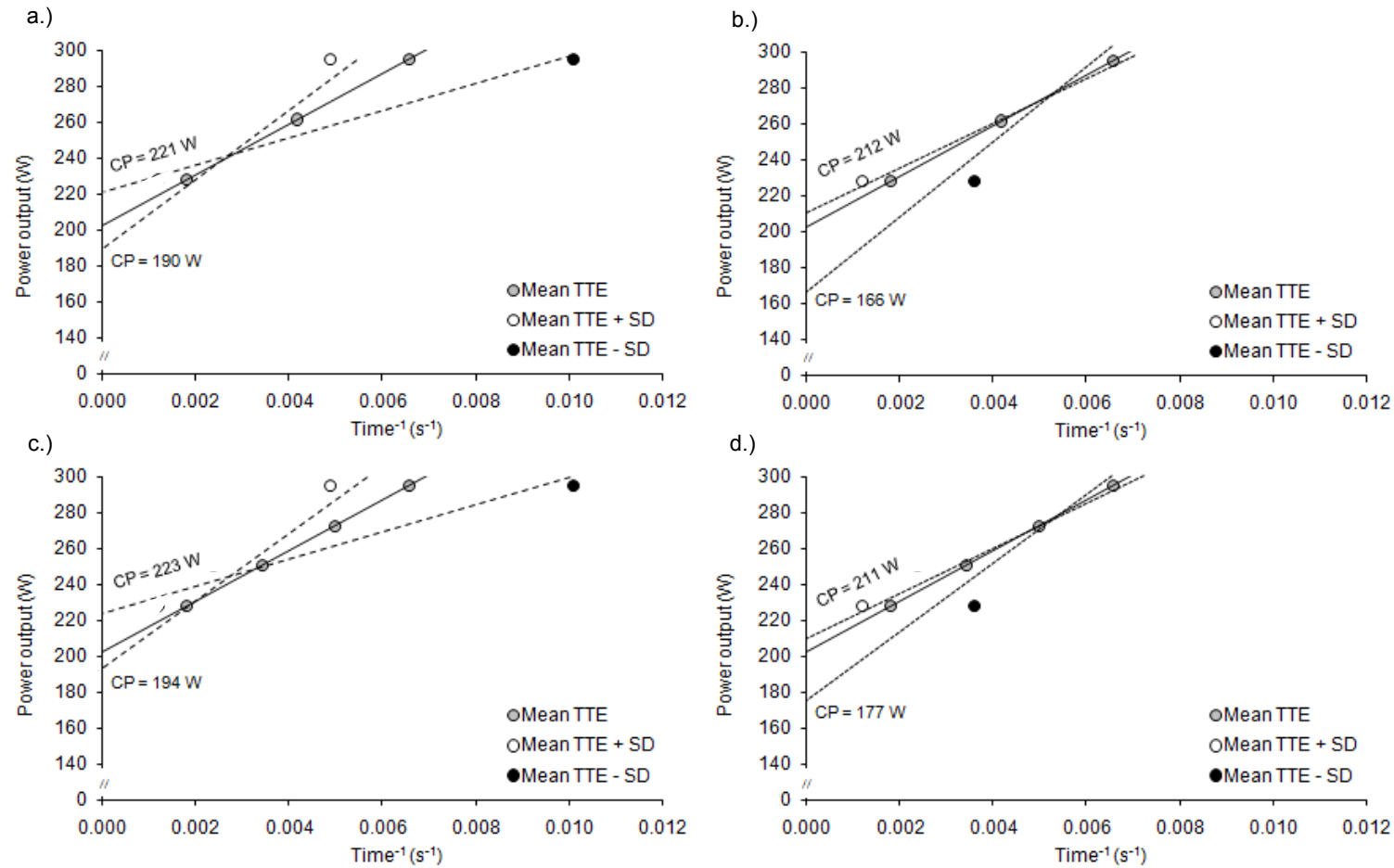
Figure 6.7: Different Critical Power estimates for a.) mean TTE data for the two longer-duration data points and ± 1 SD for the short-duration data point; b.) mean TTE data for the two shorter-duration data points and ± 1 SD for the long-duration data point ± 1 SD; c.) mean TTE data for the three longer-duration data points and ± 1 SD for the short-duration data point; b.) mean TTE data for the three shorter-duration data points and ± 1 SD for the long-duration data point ± 1 SD

It is acknowledged that the practical implications of the models illustrated in figures 6.6 and 6.7 are limited by the long- and short-duration data originating from different participants, as well as by the additional P-t$^{-1}$ data points for the three- and four-point models having been generated mathematically rather than collected experimentally. However, it is clear from the two-point models in figure 6.6 that one data point lying 1 SD from the mean may lead to a large change in CP (i.e., up to 55 W in the examples illustrated), compared with the CP estimate derived from mean TTE values. However, using three- and four-point models reduced this change in the CP estimate to 37 and 26 W, respectively. In addition to this improvement, three- and four-point models generate useful r values, unlike two-point models that will always produce r = 1.00. It is worth noting that for the three- and four-point models displayed in figure 6.7, r > 0.99 when CP was equal to 211 and 212 W (i.e., within 10 W of the original CP estimate of 203 W) and r = 0.97 when CP was equal to 221 W (i.e., 18 W greater than the original estimate). For all other models, r < 0.96 (i.e., when the CP estimate was ≥ 20 W away from the original estimate of 203 W). This demonstrates the sensitivity of r and shows that a criterion value of r > 0.97 ought to significantly reduce error in the CP estimate.

*6.4.4) Conclusions*

The current study is the first to monitor the effects of 10, repeated short- and long-duration TTE trials used for CP determination. The results have revealed that short-duration fixed power TTE trials (lasting ~ 2.5 min) can be expected to produce trial-to-trial variation of ~ 3.5 – 10.5 % and that longer duration TTE trials (lasting ~ 9 min) may vary by 12.1 – 31.7 %. The variation for both short- and long-duration trials does not appear to decline over the first few trials and, as such, a fixed number of familiarisation trials prior to CP determination are not recommended. Instead, in order to achieve a valid estimate of CP, it is recommended that a minimum of three data points are used, a high level of control of any extraneous variables is achieved during each trial and that an excellent linear fit to the P-t$^{-1}$ model is obtained (i.e., r > 0.97).

# 7) Critical Power in Different Fitness Groups

## 7.1) Introduction

A number of parameters were identified in chapter 1 as representative of aerobic fitness, including LT, $\dot{V}O_{2max}$, economy or efficiency and $\dot{V}O_2$ kinetics. In terms of fitness markers, perhaps most commonly cited are the short-term responses of LT and $\dot{V}O_{2max}$ to training, which have been reported to increase concurrently following 5 – 8 weeks of constant-load exercise (Edge *et al.*, 2006; Poole & Gaesser, 1985). In addition, trained athletes elicit higher $\dot{V}O_{2max}$ values compared with untrained individuals (Morgan *et al.*, 1995), but a closer look at the literature shows that $\dot{V}O_{2max}$ is less able to predict differences in performance among highly trained athletes (Coyle *et al.*, 1988; Jones, 1998). Therefore, factors beyond those influencing $\dot{V}O_{2max}$, which include $\dot{Q}_{max}$, SV, blood volume, blood flow and haemoglobin (Hb) content (Bassett & Howley, 2000; Saltin & Strange, 1992), appear to be important for improved aerobic performance. In the absence of a superior $\dot{V}O_{2max}$, relative LT (i.e., LT expressed as a % of $\dot{V}O_{2max}$) has been positively related to superior performance in high-level athletes (Coyle *et al.*, 1988; Jones, 1998). As such, relative LT has been identified as a marker of aerobic endurance (Joyner & Coyle, 2008) and may be affected by peripheral characteristics of muscle such as a high percentage of type I fibres, enhanced mitochondrial enzyme activity, greater fat oxidation, storage and sparing of muscle glycogen and the capacity to efficiently dissipate heat (Bassett & Howley, 2000; Bosquet *et al.*, 2002). One aim of the current study is to investigate the differences in absolute and relative measures of CP across different fitness groups, to determine whether CP may be a valid marker of aerobic fitness and/or aerobic endurance.

While LT, $\dot{V}O_{2max}$, economy or efficiency and $\dot{V}O_2$ kinetics are well-established markers of aerobic fitness (for a diagrammatical representation see figure 2 in Coyle, 1999), accurately measuring and interpreting them relies on expensive, technical laboratory equipment and scientific expertise. As such, their effective use is largely restricted to high-level sports performance, private consultation and research

environments. Although less familiar to coaches and practitioners than blood lactate- and $\dot{V}O_2$ -based parameters, CP is well-supported as an aerobic measure (Hill, 1993; Jenkins & Quigley, 1992) and correlates well with $\dot{V}O_{2max}$ , ventilatory and individual anaerobic thresholds and MLSS (McLellan & Cheung, 1992; Moritani *et al.*, 1981; Okudan & Gökbel, 2006; Pringle & Jones, 2002). The advantages of CP over other physiological-based measures are that it can be determined non-invasively and without access to specialist equipment or personnel and can, therefore, be applied across a broad range of exercisers.

Attempts have been made to clarify the physiological responses to exercise at CP using cycle ergometry and a summary of results is displayed in table 7.1. This is an extension of table 3.2 (in section 3.3) and it provides an opportunity for the relationships between CP and both LT and $\dot{V}O_{2max}$ to be explored for individuals of varying fitness levels. With data in table 7.1 showing CP values to range from 113 – 175 % of P-LT, and from 62 – 85 % of P-$\dot{V}O_{2max}$ , it is clear that CP represents an aerobic power that exceeds P-LT and is less than P-$\dot{V}O_{2max}$ within mainly young, active males. The variation in responses to exercise at CP was discussed in section 3.3 and is again illustrated in table 7.1, with TTE values of ~ 16 – 40 min, $\dot{V}O_2$ values of 68 – 97 % of $\dot{V}O_{2max}$ (when measured directly) and $[La^-]_{bl}$ responses reflecting both steady and non-steady states. The absolute value of CP does not appear to relate to whether exercise at CP elicits a steady or a non-steady state since those studies reporting no change in $[La^-]_{bl}$ towards the end of exercise at CP imposed exercise intensities (equal to CP) of 145 – 314 W (Jenkins & Quigley, 1990;1992; Poole *et al.*, 1990), while authors reporting significant changes in $[La^-]_{bl}$ imposed similar exercise intensities (at CP) of 242 – 284 W (Baron *et al.*, 2005; Brickley *et al.*, 2002; Carter *et al.*, 2005; McLellan & Cheung, 1992; Pringle & Jones, 2002). Therefore, the possibility that steady state exercise is related to a lower absolute CP, potentially due to reduced absolute metabolic stress (as was suggested in section 4.1.2 for elderly and COPD populations), is not supported.

Table 7.1: Summary of mean data taken (or calculated) from studies that have reported Critical Power (CP) relative to lactate threshold (LT) and/or $\dot{V}O_{2max}$ and/or have measured responses to exercise at (or very close to) CP (studies listed in order of ascending $\dot{V}O_{2max}$)

| Lead author (year) | n (m) | n (f) | Age (y) | $\dot{V}O_{2max}$ (L·min⁻¹) | $\dot{V}O_2$ -LT (L·min⁻¹) | P-LT (W) | CP (W) | CP (% $\dot{V}O_2$ -LT) | CP (%P-LT) | CP (%P- $\dot{V}O_{2max}$) | CP TTE (min) | $\dot{V}O_2$ at CP (% $\dot{V}O_{2max}$) | End [La⁻]bl (mmol·L⁻¹) | Δ[La⁻]bl (mmol·L⁻¹) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Moritani (1981) | - | 8 | 21 | 2.4 | 1.6 | - | 145 | 93 | - | - | - | 60est | - | - |
| Okudan (2006) | 30 | - | 20 | 2.7 | 1.6VT | 106VT | 168 | - | 158 | 85 | 22 | - | - | - |
| Overend (1992) | 13 | - | 24 | 3.3 | - | - | 177 | - | - | 62 | > 24 | 85end | 8.2 | 0.4 |
| Jenkins (1992) | 6 | - | 19 | 3.4 | - | - | 215 | - | - | - | < 40 | 77mean | 9.5 | NS |
| Jenkins (1992) | 6 | - | 19 | 3.5 | - | - | 226 | - | - | - | < 40 | 77mean | 10.6 | NS |
| Dekerle (2003) | 11 | - | 23 | 3.5 | 1.9VT | 159VT | 278 | 161 | 175 | 83 | - | 85est | - | - |
| Baron (2005) | 8 | - | 23 | 3.5 | - | - | 284 | - | - | 80 | 22 | 90end | 13.8 | 3.8 |
| Jenkins (1992) | 12 | - | 19 | 3.7 | - | - | 196 | - | - | - | < 40 | 68mean | 8.2 | NS |
| Moritani (1981) | 8 | - | 26 | 3.7 | 2.3 | - | 204 | 113 | - | - | - | 68est | - | - |
| Pringle (2002) | 7 | 1 | 25 | 3.7 | 2.1 | 154 | 242 | - | 158 | 71 | 22 | 89end | - | 1.2 |
| Poole (1990) | 8 | - | 22 | 3.8 | 1.7 | 120 | 197 | 174 | 167 | 69 | > 24 | 79end | 5.6 | NS |
| Jenkins (1992) | 12 | - | 19 | 3.9 | - | - | 255 | - | - | - | < 40 | 81mean | 10.8 | NS |
| McLellan (1992) | 14 | - | 23 | 4.1 | 3.0 | 235 | 265 | 113 | 113 | - | 21 | 87end | 6.8 | 1.8 |
| Carter (2005) | 8 | 3 | 30 | 4.1 | 2.3VT | 167VT | 278 | 171 | 166 | 83 | 16 | 97end | 9.2 | 3.2 |
| Poole (1990) | 8 | - | 22 | 4.4 | 2.1 | 166 | 217 | 159 | 132 | 67 | > 24 | 79end | 4.2 | NS |
| Brickley (2002) | 7 | - | 23 | 4.6 | - | - | 273 | - | - | 67 | 30 | 91end | 7.3 | 2.2 |
| Jenkins (1990) | 8 | - | 22 | 5.1 | - | - | 314 | - | - | - | < 30 | - | 8.9 | NS |

$\dot{V}O_2$ -LT: $\dot{V}O_2$ at lactate threshold (or ventilatory threshold [VT]); P-LT: power at lactate threshold (or ventilatory threshold [VT]); P- $\dot{V}O_{2max}$: power associated with the attainment of $\dot{V}O_{2max}$; CP TTE: time to exhaustion at Critical Power; $\dot{V}O_2$ at CP: measured by indirect estimation from the sub-maximal linear power- $\dot{V}O_2$ relationship (est), at the end of exercise at Critical Power (end), or as an average during exercise at Critical Power (mean); End [La⁻]bl: blood lactate concentration at the end of exercise at Critical Power; Δ[La⁻]bl: change in blood lactate concentration from (at least) 5 min to the end of exercise at Critical Power; NS: not significant

The correlations calculated from the data in table 7.1 between CP (measured in W) and $\dot{V}O_2$-LT (r = 0.65), P-LT (r = 0.71) and $\dot{V}O_{2max}$ (r = 0.74) suggest that CP will be higher in groups with improved aerobic fitness. In addition, the correlation between relative CP (i.e., CP as a % of P-$\dot{V}O_{2max}$) and relative LT (r = 0.75) implies that relative CP may be a useful determinant of endurance performance. However, other than to conclude that P-LT < CP < P-$\dot{V}O_{2max}$, the homogeneity of the populations represented in the literature (i.e., mainly young, active males), combined with the variation in responses to exercise at CP, limits our understanding of the physiological characteristics of CP over a range of fitness levels. Therefore, the aims of the present study are three-fold:

1. To determine the relationships between LT, CP and $\dot{V}O_{2max}$ for different fitness groups;
2. To establish whether TTE at and around CP is the same for different fitness groups;
3. To investigate the physiological responses ($\dot{V}O_2$, [La$^-$]$_{bl}$ and HR) at and around CP for different fitness groups.

As has been used in previous experimental studies (Baldwin *et al.*, 2000; Proctor *et al.*, 1995; Tomlin & Wenger, 2002), $\dot{V}O_{2peak}$ will be used in the present study to differentiate aerobic fitness groups. If CP is a valid physiological parameter that defines an exercise-intensity domain, or boundary between two domains, then the TTE and physiological responses at and around CP ought to be similar, regardless of $\dot{V}O_{2peak}$. Based on this rationale, and the literature presented in the current and previous sections, the following hypotheses have been formed:

1. The power output and $\dot{V}O_2$ at CP will be greater than those at LT and less than MMP/$\dot{V}O_{2peak}$ for all groups;
2. The $\dot{V}O_2$ (as a % of $\dot{V}O_{2peak}$), [La$^-$]$_{bl}$ (mmol·L$^{-1}$) and HR (as a % of HR$_{peak}$) will continue to rise during exercise at and above CP for all groups;
3. The $\dot{V}O_2$ (as a % of $\dot{V}O_{2peak}$) and [La$^-$]$_{bl}$ (mmol·L$^{-1}$) will attain a delayed steady state during exercise below CP for all groups.

## 7.2) Methods and procedures

### 7.2.1) Participants

Twenty-five healthy, non-smoking males (aged 19 – 44 y) were recruited to take part in the present study. Based on $\dot{V}O_{2peak}$ values measured during an initial RAMP, individuals were assigned to one of three fitness groups: LOW (< 41 mL·kg$^{-1}$·min$^{-1}$), MOD (43 – 50 mL·kg$^{-1}$·min$^{-1}$), and HIGH (> 57 mL·kg$^{-1}$·min$^{-1}$). Mean ± SD descriptive data are displayed in table 7.2. There were no significant differences between groups for age, height or body mass (P > 0.05).

Table 7.2: Mean ± SD descriptive data for the three fitness groups and all participants combined

|  | n | Age (y) | Height (cm) | Body Mass (kg) | $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$) |
|---|---|---|---|---|---|
| LOW | 9 | 32.0 ± 4.6 | 174 ± 6 | 79.6 ± 11.3 | 34.9 ± 4.4 |
| MOD | 8 | 32.8 ± 7.2 | 178 ± 5 | 82.7 ± 10.8 | 46.1 ± 1.9 |
| HIGH | 8 | 32.4 ± 8.8 | 173 ± 7 | 69.3 ± 7.9 | 63.6 ± 4.0 |
| Combined | 25 | 32.4 ± 6.7 | 175 ± 6 | 77.3 ± 11.3 | 47.6 ± 12.6 |

No significant differences between groups

### 7.2.2) Experimental overview

The current experiment involved eight or nine separate visits to the laboratory. Participants initially performed an LT test followed by a RAMP and the two tests were separated by 5 min of light, active recovery. On the same initial visit to the laboratory and following recovery from the RAMP, participants completed a TTE familiarisation trial at 100 % of MMP. The P-t$^{-1}$ data collected in the familiarisation trial was used to help set subsequent fixed power outputs for the CP determination trials. The four or five subsequent laboratory visits each involved a constant-load TTE cycling test for the determination of CP. Following the LT, RAMP and CP determination tests, participants completed three final TTE tests on separate days at intensities equal to 95, 100 and 105 % of CP. These intensities were based upon previous studies that have used 105 % of CP to investigate responses to exercise

above CP (Hill *et al.*, 2002; Poole *et al.*, 1988; Poole *et al.*, 1990) and were presented in a random order. Due to the amount of data generated within this study the results have been separated into two discrete parts: part 1 reports data from the LT, RAMP and CP determination tests; part 2 reports data from the trials at, above and below CP.

*7.2.3) Cycle ergometer*

All tests were performed on a Lode cycle ergometer (see section 5.6.1). The seat and handlebar positions remained constant throughout all tests for each individual. Participants chose between wearing their own cycling shoes with clip-in pedals or wearing trainers with conventional metal pedals and toe straps. The chosen pedal system remained constant for each individual throughout all tests.

*7.2.4) Lactate threshold and incremental ramp tests*

On the initial laboratory visit each participant completed an LT test. During the warm-up period of the LT test participants were instructed to self-select their cadence (see section 5.6.2). The LT was assessed as described in section 5.7.1 and a typical $[La^-]_{bl}$ response is displayed in figure 7.1. On terminating the LT test participants continued to cycle at 50 W for 5 min. A low-intensity active recovery was chosen in order to maintain blood flow and $O_2$ supply in the tissues, hence facilitating recovery (Dodd *et al.*, 1984). The RAMP followed the active recovery period, as described in see section 5.8, and MMP was calculated from the power output attained during the final minute of exercise *(equation 6)*. The $\dot{V}O_{2peak}$ was measured using the Douglas bag method described in section 5.8.2.
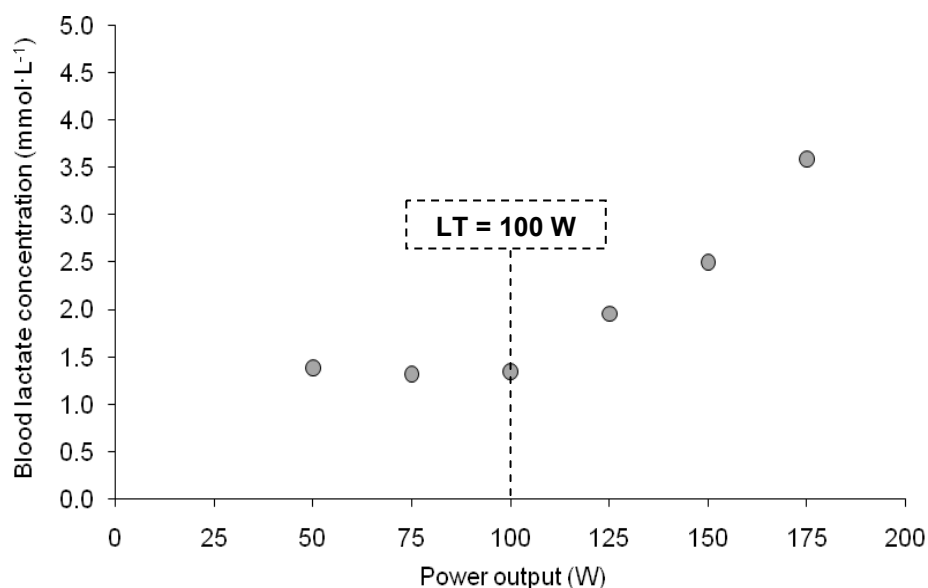
Figure 7.1: An example of lactate threshold (LT) identification following the LT test

*7.2.5) Time to exhaustion tests for Critical Power determination*

The CP determination trials were completed as described in section 5.10.2. Tests lasting < 3 min or > 15 min were rejected (this occurred on only two out of 100 trials) and participants completed a fifth test at a re-calculated power output if necessary. An example of a P-t$^{-1}$ relationship for one participant is displayed in figure 7.2. The linear relationship between P and t$^{-1}$ produced a mean fit of r = 0.99 ± 0.003 (range: 0.97 – 1.00) and a mean standard error of the estimate (SEE)[3] for CP of 3.5 ± 0.58 W (range: 0.02 – 7.14 W). The $\dot{V}O_2$ -CP$_{est}$ was calculated according to the methods described in section 5.10.4.

*7.2.6) Time to exhaustion tests at and around Critical Power*

Following CP determination all participants completed TTE tests at 95, 100 and 105 % of CP in a random order, separated by at least 48 h. Prior to the test a resting blood sample was collected and analysed for [La$^-$]$_{bl}$. Participants warmed up for 5 min at 20 % of MMP and the exhaustive effort followed immediately. Expired air, blood samples, HR and RPE scores were collected during every fifth minute of exercise and

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[3] The SEE was calculated for each individual according to the methods described by Vincent (2005): SEE = $\sqrt{[\Sigma(Y – Y')^2/n]}$, where Y represents the measured power output, Y' represents the power output predicted from the linear regression equation and n represents the number of data points (or trials).

additional end-exercise HR and $[La^-]_{bl}$ measures were recorded. The test duration was capped at 60 min (i.e., participants stopped cycling after 60 min if they had not already done so) and this occurred on seven out of 75 trials (five participants completed 60 min at 95 % of CP, one of whom also completed 60 min at 100 and 105 % of CP).
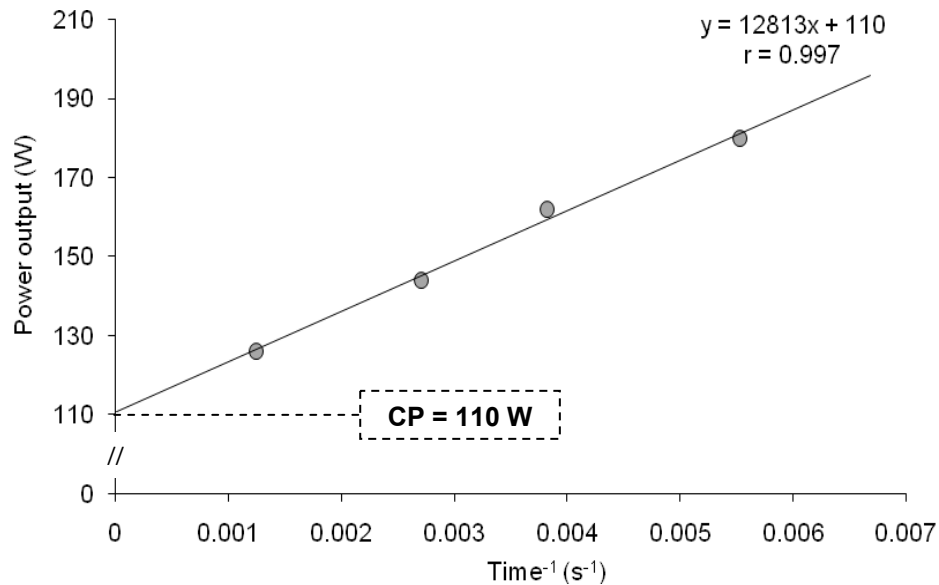


Figure 7.2: An example of Critical Power (CP) determination

*7.2.7) Data analyses*

Descriptive statistics are expressed as mean ± SD and tests of difference are reported as mean ± SEM. Statistical analyses were carried out using SPSS 14.0 and the level of significance was set at $P < 0.05$. A one-way between-groups ANOVA was used to compare the three fitness groups (LOW, MOD and HIGH) for the dependent variables obtained from the LT, RAMP and CP determination trials. Homogeneity of variance was checked using the Levene statistic and a post-hoc Tukey test was used to localise the between-group differences. Pearson's correlation coefficients were used to determine relationships between variables for the three fitness groups and for the whole sample population (n = 25).

A two-way between-within repeated-measures ANOVA was used to identify differences and interactions between (i) the fitness groups and the tests at 95, 100 and

105 % of CP for power output and TTE variables, and (ii) the fitness groups and the changes over time for $\dot{V}O_2$, $[La^-]_{bl}$ and HR. Sphericity was checked using Mauchly's test and the Greenhouse-Geisser correction was used for epsilon < 0.75, while the Huynh-Feldt correction was adopted for less severe asphericity (> 0.75). Within-subject differences were localised using pair-wise comparisons with a Bonferroni adjustment and between-group differences were localised using a post-hoc Tukey test and a further simple ANOVA where two time factors were involved.

## 7.3) Results: Part 1 – Identifying Critical Power for different fitness groups

The current section compares the LOW, MOD and HIGH fitness groups with respect to a) P-LT, CP and MMP, and b) $\dot{V}O_2$ -LT, $\dot{V}O_2$ -$CP_{est}$ and $\dot{V}O_{2peak}$.

### 7.3.1) Critical Power determination trials

All CP determination trials were performed at work rates between 70 and 110 % of MMP. The lowest and highest work rates were (mean ± SD) 78 ± 5 and 102 ± 5 % of MMP for the LOW group, 81 ± 3 and 106 ± 5 % of MMP for the MOD group and 82 ± 3 and 105 ± 5 % of MMP for the HIGH group, respectively. The corresponding shortest and longest times to exhaustion were 3 min 37 s and 13 min 01 s for LOW, 3 min 12 s and 11 min 54 s for MOD and 3 min 01 s and 13 min 37 s for HIGH. The peak HR attained during all CP determination trials was (mean ± SD) 97 ± 2, 96 ± 3 and 95 ± 3 % of $HR_{peak}$ for the LOW, MOD and HIGH groups, respectively.

### 7.3.2) Power output at lactate threshold, Critical Power and maximal minute power

Power outputs at LT, CP and MMP for the three fitness groups are presented in table 7.3. In addition to the mean ± SEM data, minima and maxima have been displayed to represent the ranges for each parameter for the combined population group (n = 25). The CP (measured in W) was higher than P-LT but lower than MMP for all fitness groups (P < 0.05). Despite a tendency for the MOD group to demonstrate higher P-LT, CP and MMP values (measured in W) than the LOW group, these differences were not statistically significant (P > 0.05). However, the HIGH group elicited higher

values for all three power variables (measured in W) compared with the LOW and MOD groups ($P < 0.05$). The CP expressed as a % of MMP (relative CP) was higher than the P-LT expressed as a % of MMP (relative P-LT) for all fitness groups ($P < 0.05$). While the relative P-LT was not different between fitness groups ($P > 0.05$), relative CP was lower for the LOW group compared with the HIGH group ($P = 0.001$).

*7.3.3) The $\dot{V}O_2$ at lactate threshold, Critical Power and $\dot{V}O_{2peak}$*

Table 7.3 shows that $\dot{V}O_2$-$CP_{est}$ (measured in $mL \cdot kg^{-1} \cdot min^{-1}$) was higher than $\dot{V}O_2$-LT but lower than $\dot{V}O_{2peak}$ for all fitness groups ($P < 0.05$). In addition, $\dot{V}O_2$-$CP_{est}$ (measured in $mL \cdot kg^{-1} \cdot min^{-1}$) was significantly different across the three fitness groups ($P < 0.05$). By comparison, $\dot{V}O_2$-LT ($mL \cdot kg^{-1} \cdot min^{-1}$) was not different between the LOW and MOD groups ($P > 0.05$). The $\dot{V}O_2$-$CP_{est}$ expressed as a % of $\dot{V}O_{2peak}$ (relative $\dot{V}O_2$-$CP_{est}$) was higher than the $\dot{V}O_2$-LT expressed as a % of $\dot{V}O_{2peak}$ (relative $\dot{V}O_2$-LT) for all fitness groups ($P < 0.05$). In addition, relative $\dot{V}O_2$-$CP_{est}$ was lower for the LOW and MOD groups compared with the HIGH group ($P < 0.05$). By comparison, relative $\dot{V}O_2$-LT was only lower for the MOD group compared with the HIGH group ($P = 0.042$). The size of $\Delta$ was smaller for the LOW group compared with the two other fitness groups ($P < 0.05$) but $\dot{V}O_2$-$CP_{est}$ expressed as a % of $\Delta$ was not different between groups ($P > 0.05$).

*7.3.4) Relationships between power output and $\dot{V}O_2$ variables*

The CP expressed in W was significantly correlated with absolute measurements of P-LT, $\dot{V}O_2$-LT and $\dot{V}O_{2peak}$ ($n = 25$, $r > 0.70$, $P < 0.001$; figure 7.3) and $\dot{V}O_2$-$CP_{est}$ expressed in $mL \cdot kg^{-1} \cdot min^{-1}$ was significantly correlated with both $\dot{V}O_2$-LT ($n = 25$, $r = 0.91$, $P < 0.05$) and $\dot{V}O_{2peak}$ ($n = 25$, $r = 0.96$, $P < 0.05$) expressed in $mL \cdot kg^{-1} \cdot min^{-1}$. No significant relationships were identified between relative CP and relative P-LT ($n = 25$, $r = 0.24$, $P = 0.251$) or between relative $\dot{V}O_2$-$CP_{est}$ and relative $\dot{V}O_2$-LT ($n = 25$, $r = 0.25$, $P = 0.236$). An expansive summary of correlations between the LT, CP, $\dot{V}O_{2peak}$ and MMP variables (for $n = 25$) are included in *Appendix G*.

Table 7.3: Mean ± SEM power output and $\dot{V}O_2$ data for the three fitness groups (LOW, MOD and HIGH) and all participants combined (n = 25)

| | | LOW | MOD | HIGH | Combined | Range Min | Range Max |
|---|---|---|---|---|---|---|---|
| Power output (W) | P-LT | $114 \pm 13^{*\theta}$ | $138 \pm 13^{*\theta}$ | $191 \pm 9^{\theta}$ | $146 \pm 9^{\theta}$ | 50 | 225 |
| | CP | $175 \pm 10^{*}$ | $211 \pm 10^{*}$ | $277 \pm 17$ | $219 \pm 11$ | 110 | 362 |
| | MMP | $256 \pm 13^{*\theta}$ | $293 \pm 13^{*\theta}$ | $358 \pm 17^{\theta}$ | $300 \pm 12^{\theta}$ | 180 | 430 |
| Power output (% of MMP) | P-LT | $45 \pm 4^{\theta}$ | $46 \pm 2^{\theta}$ | $54 \pm 2^{\theta}$ | $48 \pm 2^{\theta}$ | 18 | 66 |
| | CP | $68 \pm 2^{*}$ | $72 \pm 1$ | $77 \pm 2$ | $72 \pm 1$ | 61 | 84 |
| $\dot{V}O_2$ (mL·kg$^{-1}$·min$^{-1}$) | $\dot{V}O_2$-LT | $17.2 \pm 1.2^{*\theta}$ | $21.4 \pm 0.9^{*\theta}$ | $35.1 \pm 1.8^{\theta}$ | $24.3 \pm 1.7^{\theta}$ | 10.3 | 42.9 |
| | $\dot{V}O_2$-CP$_{est}$ | $24.6 \pm 1.4^{*\dagger}$ | $32.7 \pm 1.0^{*}$ | $51.0 \pm 1.4$ | $35.6 \pm 2.4$ | 19.0 | 55.7 |
| | $\dot{V}O_{2peak}$ | $34.9 \pm 1.5^{*\dagger\theta}$ | $46.1 \pm 0.7^{*\theta}$ | $63.6 \pm 1.4^{\theta}$ | $47.6 \pm 2.5^{\theta}$ | 26.8 | 69.0 |
| $\dot{V}O_2$ (% of $\dot{V}O_{2peak}$) | $\dot{V}O_2$-LT | $49 \pm 3^{\theta}$ | $46 \pm 2^{*\theta}$ | $55 \pm 2^{\theta}$ | $50 \pm 1^{\theta}$ | 37 | 66 |
| | $\dot{V}O_2$-CP$_{est}$ | $71 \pm 2^{*}$ | $71 \pm 2^{*}$ | $80 \pm 2$ | $74 \pm 2$ | 60 | 88 |
| $\Delta$ (mL·kg$^{-1}$·min$^{-1}$) | $\dot{V}O_{2peak} - \dot{V}O_2$-LT | $17.7 \pm 1.0^{*\dagger}$ | $24.7 \pm 0.9$ | $28.5 \pm 1.4$ | $23.4 \pm 1.1$ | 13.2 | 33.6 |
| $\dot{V}O_2$ (% of $\Delta$) | $\dot{V}O_2$-CP$_{est}$ | $41 \pm 6$ | $45 \pm 4$ | $55 \pm 5$ | $47 \pm 3$ | 10 | 75 |

Min: minimum individual value recorded; Max: maximum individual value recorded
Significantly different from HIGH: * $P < 0.05$; significantly different from MOD: $^{\dagger}$ $P < 0.001$; significantly different from the CP parameter: $^{\theta}$ $P < 0.001$
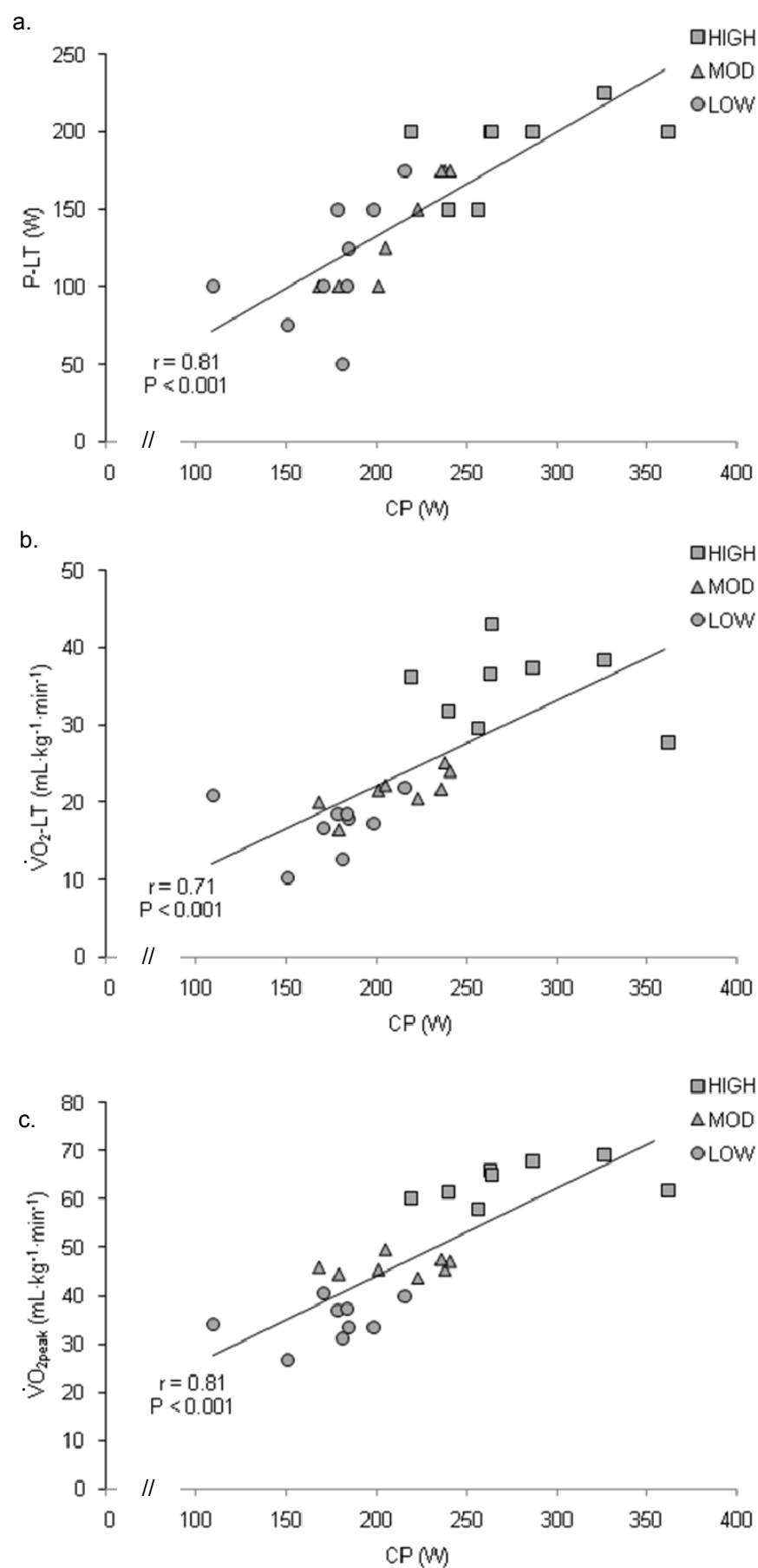
Figure 7.3: CP (W) versus a.) P-LT, b.) V̇O₂ -LT and c.) V̇O₂peak for all participants (n = 25)

**7.4) Discussion: Part 1 – Identifying Critical Power for different fitness groups**

The purpose of part 1 of the present study was to determine the relationships between a) P-LT, CP and MMP, and b) $\dot{V}O_2$-LT, $\dot{V}O_2$-$CP_{est}$ and $\dot{V}O_{2peak}$ for groups categorised according to $\dot{V}O_{2peak}$. The data presented in table 7.3 support the first experimental hypothesis stated in section 7.1, whereby:

1. The power output at CP (W) was greater than P-LT and less than MMP for all groups;

2. The $\dot{V}O_2$-$CP_{est}$ was greater than $\dot{V}O_2$-LT and less than $\dot{V}O_{2peak}$ for all groups (when $\dot{V}O_2$ was expressed in mL·kg$^{-1}$·min$^{-1}$).

One of the main aims of part 1 was to establish whether CP is a valid marker of aerobic fitness across a range of populations. With P-LT lower than CP and CP lower than MMP, as well as absolute $\dot{V}O_2$ increasing progressively at $\dot{V}O_2$-LT, $\dot{V}O_2$-$CP_{est}$ and $\dot{V}O_{2peak}$ for the LOW, MOD and HIGH groups, it appears that CP relates similarly to the two key parameters that define the moderate, heavy and severe exercise-intensity domains (i.e., LT and $\dot{V}O_{2max}$), irrespective of $\dot{V}O_{2peak}$ categorisation. Furthermore, the strong correlations between CP and $\dot{V}O_2$-LT, P-LT and $\dot{V}O_{2peak}$ support CP as a marker of aerobic fitness and are consistent with previous studies that have reported significant correlations between CP and both anaerobic thresholds and $\dot{V}O_{2max}$ (McLellan & Cheung, 1992; Moritani *et al.*, 1981; Okudan & Gökbel, 2006).

Figure 7.4*a* shows the differences in the $\dot{V}O_2$ parameters between the three fitness groups. Unlike $\dot{V}O_2$-LT, $\dot{V}O_2$-$CP_{est}$ was significantly different between the LOW and MOD groups. This suggests that the $\dot{V}O_2$-$CP_{est}$ parameter is more effective than $\dot{V}O_2$-LT in distinguishing groups with different $\dot{V}O_{2peak}$ values. Since both $\dot{V}O_2$-LT and $\dot{V}O_2$-$CP_{est}$ were obtained from the linear sub-maximal relationship between power output and $\dot{V}O_2$, the increased sensitivity of $\dot{V}O_2$-$CP_{est}$ to differences in $\dot{V}O_{2peak}$ may be due to the increased accuracy of estimating CP (i.e., to the nearest 1 W), compared with P-LT (i.e., to the nearest 25 W). Rather than any physiological

differences, therefore, the confounding results may be due to methodological limitations of LT testing.

Figure 7.4*b* shows the changes in relative $\dot{V}O_2$ between the three fitness groups and it can be seen that relative LT did not differ between groups. While some researchers have shown relative lactate-based thresholds to be effective in distinguishing a wide range of conditioning levels, with lower fitness groups characterised by lower relative thresholds (Costill, 1970; Londeree, 1986), the work of Edge *et al.* (2006) and Duffield *et al.* (2006) support the current findings as they reported training to have no significant effect on relative LT. This was due to concomitant improvements in the absolute measures of both LT and $\dot{V}O_{2max}$ and questions the validity of relative LT as a predictor of aerobic fitness within sub-elite populations. By contrast, the current study is the first to report relative $\dot{V}O_2$ -$CP_{est}$ across fitness groups and, with higher values in the HIGH group compared with the LOW and MOD groups, the parameter may be considered a useful marker of aerobic fitness.
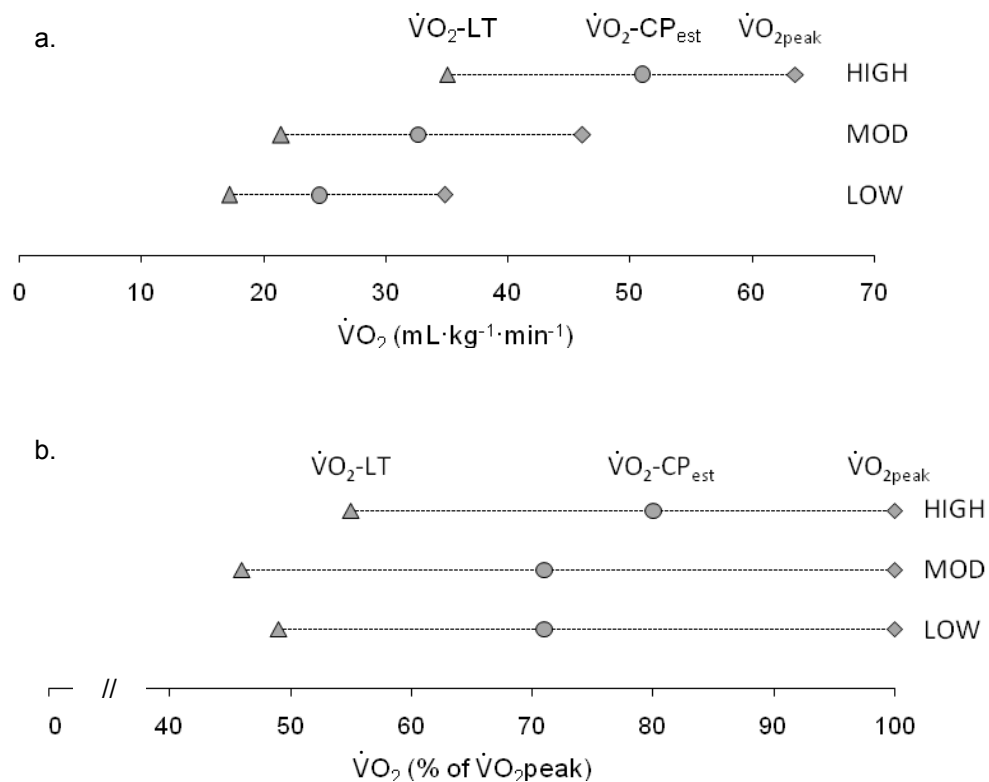


Figure 7.4: Relationships between $\dot{V}O_2$ at lactate threshold ($\dot{V}O_2$ -LT), estimated $\dot{V}O_2$ at Critical Power ($\dot{V}O_2$ -$CP_{est}$) and $\dot{V}O_{2peak}$ for the LOW, MOD and HIGH fitness groups expressed a.) in mL·kg$^{-1}$·min$^{-1}$, and b.) as a % of $\dot{V}O_{2peak}$

A closer look at figure 7.4$a$ illustrates the differences in $\Delta$ (mL·kg$^{-1}$·min$^{-1}$) between fitness groups, as reported in table 7.3. The absolute magnitude of $\Delta$ was not different for the MOD and HIGH groups and this appears to be due to concomitant increases in $\dot{V}O_2$-LT and $\dot{V}O_{2peak}$ (i.e., a rightward shift of the $\Delta$ range on the x-axis). By contrast, the significantly smaller $\Delta$ of the LOW group appears to be due to a relatively larger reduction in $\dot{V}O_{2peak}$ compared with the reduction in $\dot{V}O_2$-LT from MOD to LOW. This relative shift implies a greater limitation from central versus peripheral factors within the LOW group individuals, which would explain why $\dot{V}O_{2peak}$ differs between LOW and MOD groups but $\dot{V}O_2$-LT does not.

Figure 7.4$a$ also illustrates the lack of significant differences in $\dot{V}O_2$-CP$_{est}$ as a % of $\Delta$ between fitness groups, despite observed differences in absolute $\Delta$. While there was a tendency for $\dot{V}O_2$-CP$_{est}$ to increase from LOW to HIGH (41 $\pm$ 6 to 55 $\pm$ 5 % of $\Delta$, respectively), which presents the possibility that it may be associated with greater aerobic fitness, there was no significant correlation between $\dot{V}O_2$-CP$_{est}$ as a % of $\Delta$ and $\dot{V}O_{2peak}$ (n = 25, r = 0.31, P = 0.138). The non-significant differences between groups appear attributable to large variations in $\dot{V}O_2$-CP$_{est}$ as a % of $\Delta$ for all participants, which ranged from 10 – 75 %, and indicate that the parameter is not a valid marker of aerobic fitness. This specific aspect of analysis was not an original focus of the present investigation and requires further research, perhaps by using more distinguished fitness groups or individuals with similar $\dot{V}O_{2peak}$ values but who differ in performance capacity (i.e., aerobic endurance).

It can be concluded in the current section that a similar relationship is evident between P-LT, CP and MMP, and between $\dot{V}O_2$-LT, $\dot{V}O_2$-CP$_{est}$ and $\dot{V}O_{2peak}$, regardless of $\dot{V}O_{2peak}$. Since the methods used to determine CP adhered to the specific guidelines outlined in section 2.2.5 it is assumed that CP estimates were accurate and comparable between experimental groups. As such, initial support for the generic application of CP as a valid marker of aerobic fitness is provided. However, it is noted that certain limitations are present within the current study. For example, despite significant differences between the HIGH group and the two lower fitness groups for absolute power measures, no differences were identified between the LOW and MOD groups.

The potential impact of grouping participants into LOW, MOD and HIGH fitness groups based on $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$) will be discussed in chapter 8.

Part 1 of the current study has identified that (i) the LOW group had a lower relative CP compared with the HIGH group and (ii) the LOW group had a lower relative $\dot{V}O_2$-CP$_{est}$ as a % of $\dot{V}O_{2peak}$ compared with the HIGH group. The effect of these lower relative intensities of CP in the LOW versus HIGH fitness group may suggest that physiological responses to exercise at CP will be less severe in the LOW group. However, the lack of any significant differences in CP as a % of $\Delta$ between the fitness groups would not support this hypothesis. The next section attempts to clarify these possibilities by reporting the physiological responses to exercise at and around CP for different fitness groups.

## 7.5) Results: Part 2 – Responses at and around Critical Power for different fitness groups

The purpose of the current section is to investigate the responses to exercise below, at and above CP for the three fitness groups. The power outputs at 95, 100 and 105 % of CP were (mean ± SD) 166 ± 29, 175 ± 30 and 184 ± 32 W for the LOW group, 201 ± 28, 211 ± 30 and 222 ± 31 W for the MOD group and 263 ± 44, 277 ± 47 and 291 ± 49 W for the HIGH group, respectively. These work rates were greater for the HIGH group compared with the LOW and MOD groups (P < 0.05), but no significant differences were identified between the LOW and MOD groups (P > 0.05).

### 7.5.1) Time to exhaustion

The times to exhaustion for the three groups (and all participants combined, n = 25) are illustrated in figure 7.5. No significant differences were observed between any of the three fitness groups for TTE (min) at 100 % of CP (P > 0.05), despite a tendency for the HIGH group to demonstrate a shorter TTE compared with the other two groups (mean ± SEM: 26.5 ± 4.2, 30.0 ± 5.1 and 18.2 ± 2.7 min for the LOW, MOD and HIGH groups, respectively). This was also the case for the TTE values at 95 and 105 % of CP, whereby groups did not differ but the HIGH group showed a tendency

for TTE to be shorter (P > 0.05).  The TTE was significantly longer in trials below CP for all three fitness groups (and all participants combined) compared with the TTE at and above CP (P < 0.05).  However, while TTE was shorter during exercise at 105 % of CP for the MOD and HIGH groups compared with the TTE at CP (P < 0.05), the difference only tended to differ for the LOW group (P = 0.114).
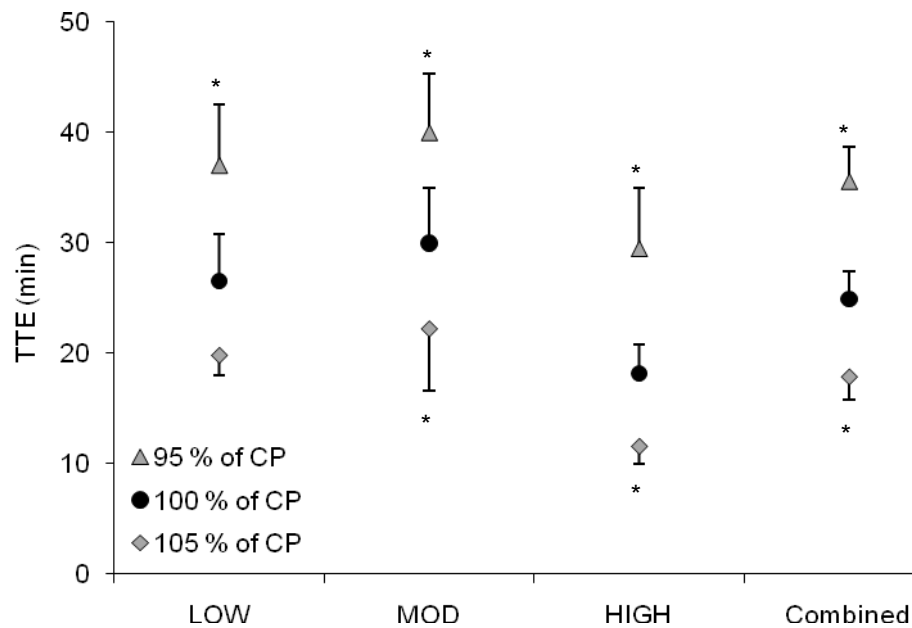


Figure 7.5: Mean ± SEM time to exhaustion (TTE) in min at 95, 100 and 105 % of Critical Power (CP)
Significantly different from the trial at 100 % of CP: * P < 0.01
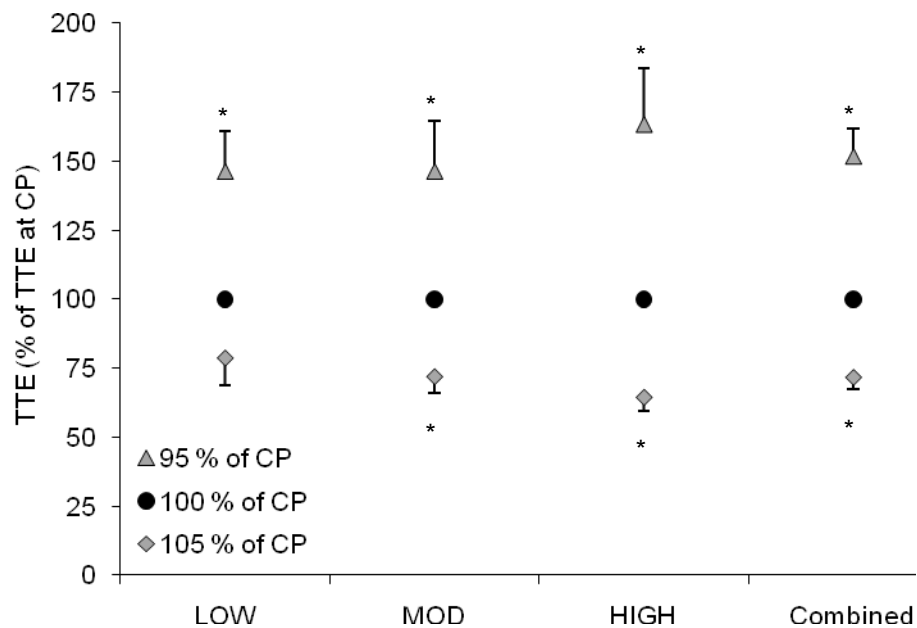


Figure 7.6: Mean ± SEM time to exhaustion (TTE) as a % of TTE at Critical Power (CP) at 95, 100 and 105 % of CP
Significantly different from the trial at 100 % of CP: * P < 0.05

Similar patterns were observed for TTE expressed as a % of the TTE at CP (figure 7.6), whereby no significant differences were observed between fitness groups (P > 0.05) but TTE differed at each intensity for all groups (P < 0.05) except between 100 and 105 % of CP in the LOW group (P = 0.069). The relationships between $\dot{V}O_{2peak}$ and TTE at CP (n = 25, r = -0.20, P = 0.335), and CP and TTE at CP (n = 25, r = -0.48, P = 0.014), are displayed in figure 7.7.
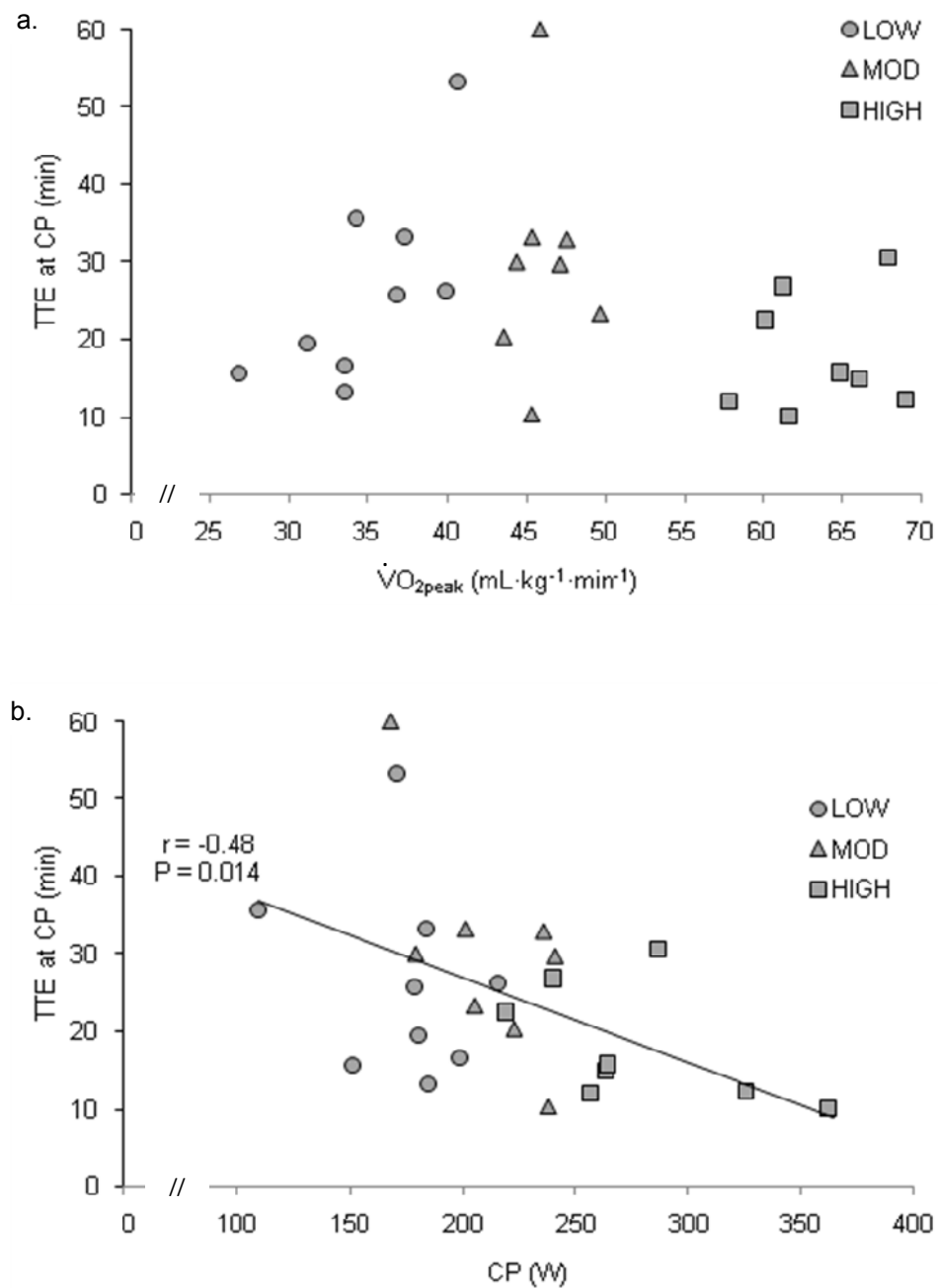


Figure 7.7: Time to exhaustion at Critical Power (TTE at CP) in min related to a.) $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$) and b.) CP (W)

*7.5.2) Physiological responses*

The $\dot{V}O_2$, $[La^-]_{bl}$ and HR values attained for each of the fitness groups at the end of exercise at 95, 100 and 105 % of CP are displayed in table 7.4. The end $\dot{V}O_2$ values (% of $\dot{V}O_{2peak}$) were not significantly different between exercise intensities or fitness groups (P > 0.05), although there was a tendency for the LOW group to elicit a higher relative $\dot{V}O_2$ at the end of each test. In support of this tendency, end $\dot{V}O_2$ was not different from $\dot{V}O_{2peak}$ for the LOW group (P > 0.05), but was significantly lower than $\dot{V}O_{2peak}$ for the MOD and HIGH groups (P < 0.05). The end-exercise $[La^-]_{bl}$ values (mmol·L$^{-1}$) were not significantly different between fitness groups at each of the three respective exercise trials (P > 0.05). End HR values (% of HR$_{peak}$) were not different between the three groups at 100 and 105 % of CP (P > 0.05), but the HIGH group demonstrated a slightly higher end HR following exercise at 95% of CP compared with the LOW group (P = 0.045).

Table 7.4: Mean ± SEM $\dot{V}O_2$, blood lactate concentration ($[La^-]_{bl}$) and heart rate (HR) data for the three fitness groups at the end of exercise at 95, 100 and 105 % of Critical Power

|  |  | LOW | MOD | HIGH |
|---|---|---|---|---|
| | 95% | 93 ± 5$^V$ | 87 ± 4 | 88 ± 3 |
| $\dot{V}O_2$ (% of $\dot{V}O_{2peak}$) | 100% | 97 ± 3$^V$ | 88 ± 3 | 89 ± 3 |
| | 105% | 96 ± 4$^V$ | 86 ± 4 | 87 ± 3 |
| | 95% | 6.26 ± 0.79 | 6.19 ± 1.27 | 6.59 ± 0.44 |
| $[La^-]_{bl}$ (mmol·L$^{-1}$) | 100% | 7.11 ± 0.60 | 7.24 ± 1.06 | 8.31 ± 0.35* |
| | 105% | 7.92 ± 0.53 | 6.89 ± 0.40 | 8.29 ± 0.58 |
| | 95% | 90 ± 1 | 93 ± 1 | 94 ± 1$^\dagger$ |
| HR (% of HR$_{peak}$) | 100% | 92 ± 2 | 94 ± 1 | 96 ± 1 |
| | 105% | 92 ± 1 | 95 ± 1 | 95 ± 1 |

Not significantly different from $\dot{V}O_{2peak}$: $^V$ P > 0.05; significantly different from the test at 95 % of Critical Power: * P < 0.05; significantly different from the LOW group: $^\dagger$ P < 0.05

The graphs presented in figure 7.8 represent the responses over time (expressed as a % of TTE) for $\dot{V}O_2$ (% of $\dot{V}O_{2peak}$), $[La^-]_{bl}$ (mmol·L$^{-1}$) and HR (% of HR$_{peak}$) during exercise at CP. There were no differences between the three fitness groups at any of the time points for any of the three physiological variables during exercise at CP ($P > 0.05$). Figures 7.9 and 7.10 represent the $\dot{V}O_2$, $[La^-]_{bl}$ and HR responses during exercise above and below CP, respectively. Due to the shorter duration of exercise at 105 % of CP, complete group data values were not available to perform statistical analyses after 20 % of total TTE, so these data points have been omitted from figure 7.9. The only group differences were identified between the LOW and HIGH fitness groups in the HR response to exercise at 105 % of CP at the 40% TTE time point ($P = 0.010$) and at 95 % of CP at all time points ($P < 0.05$).
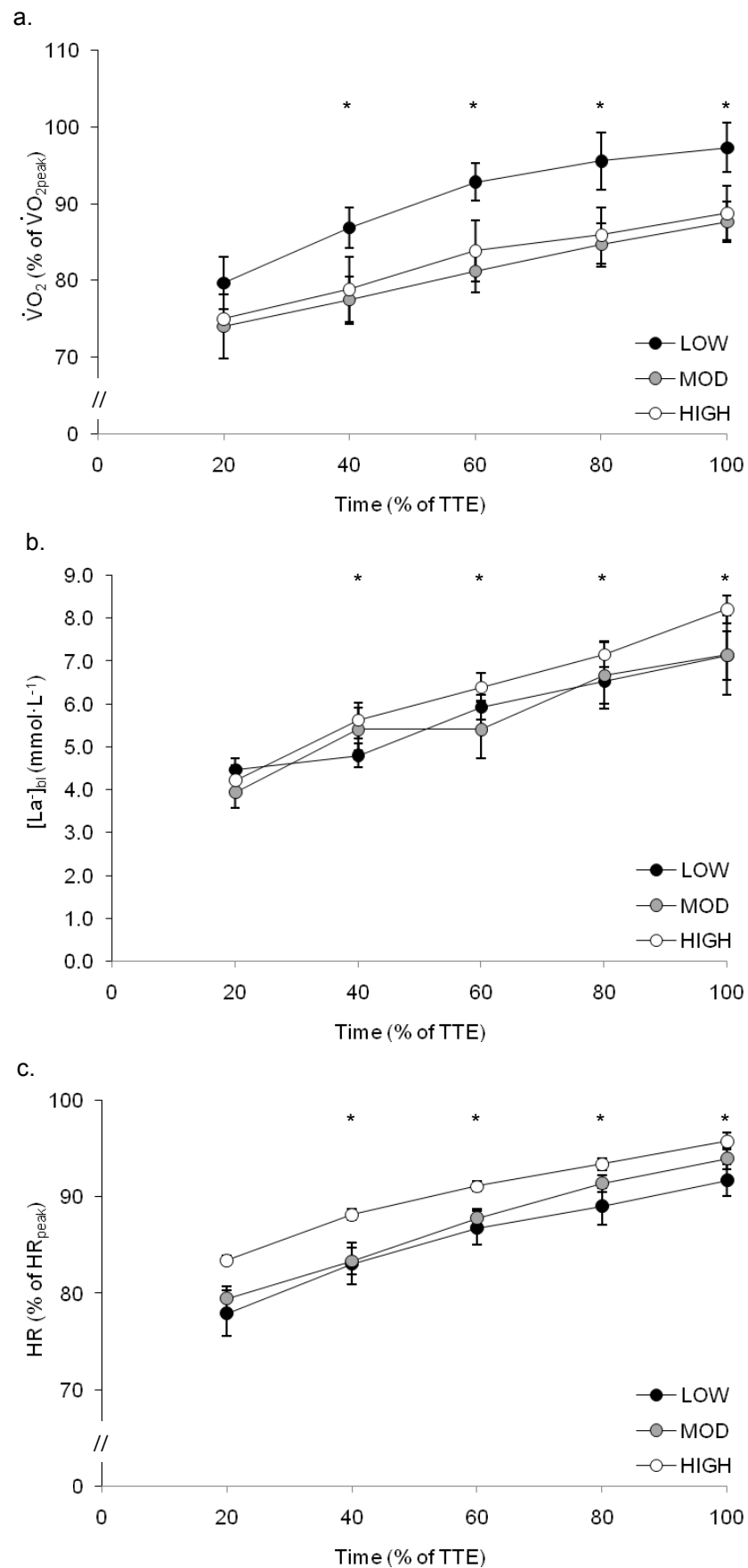
Figure 7.8: a.) $\dot{V}O_2$ , b.) blood lactate concentration ($[La^-]_{bl}$) and c.) heart rate (HR) responses to exercise at 100 % of Critical Power
Significantly greater than previous time-point (all groups): * P < 0.005
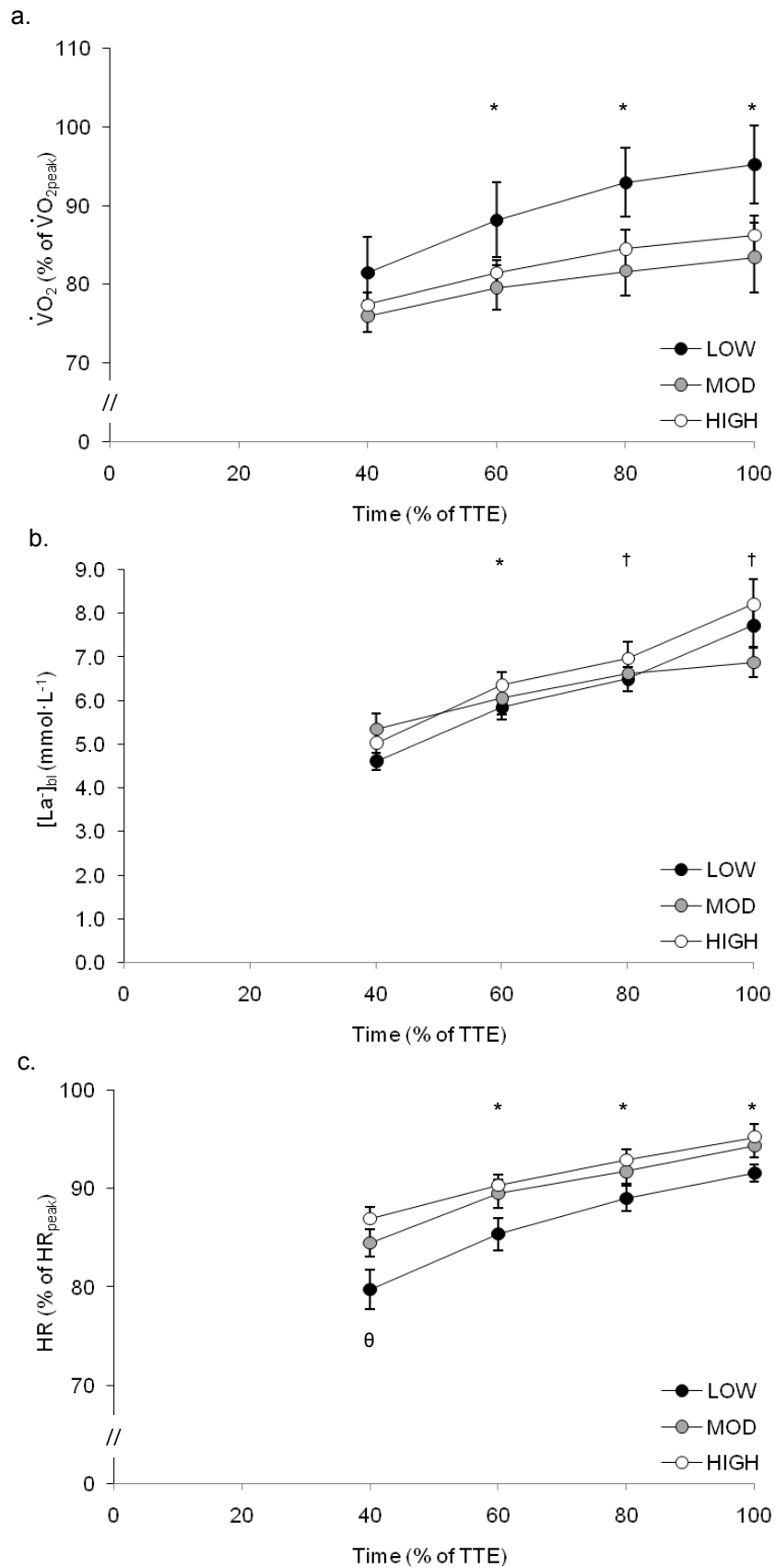
Figure 7.9: a.) $\dot{V}O_2$ , b.) blood lactate concentration ($[La^-]_{bl}$) and c.) heart rate (HR) responses to exercise at 105 % of Critical Power

Significantly greater than previous time-point (all groups): * $P < 0.05$; HIGH and LOW groups significantly greater than previous time point: $^{\dagger}$ $P < 0.05$; significantly different from HIGH group: $^{\theta}$ $P < 0.01$
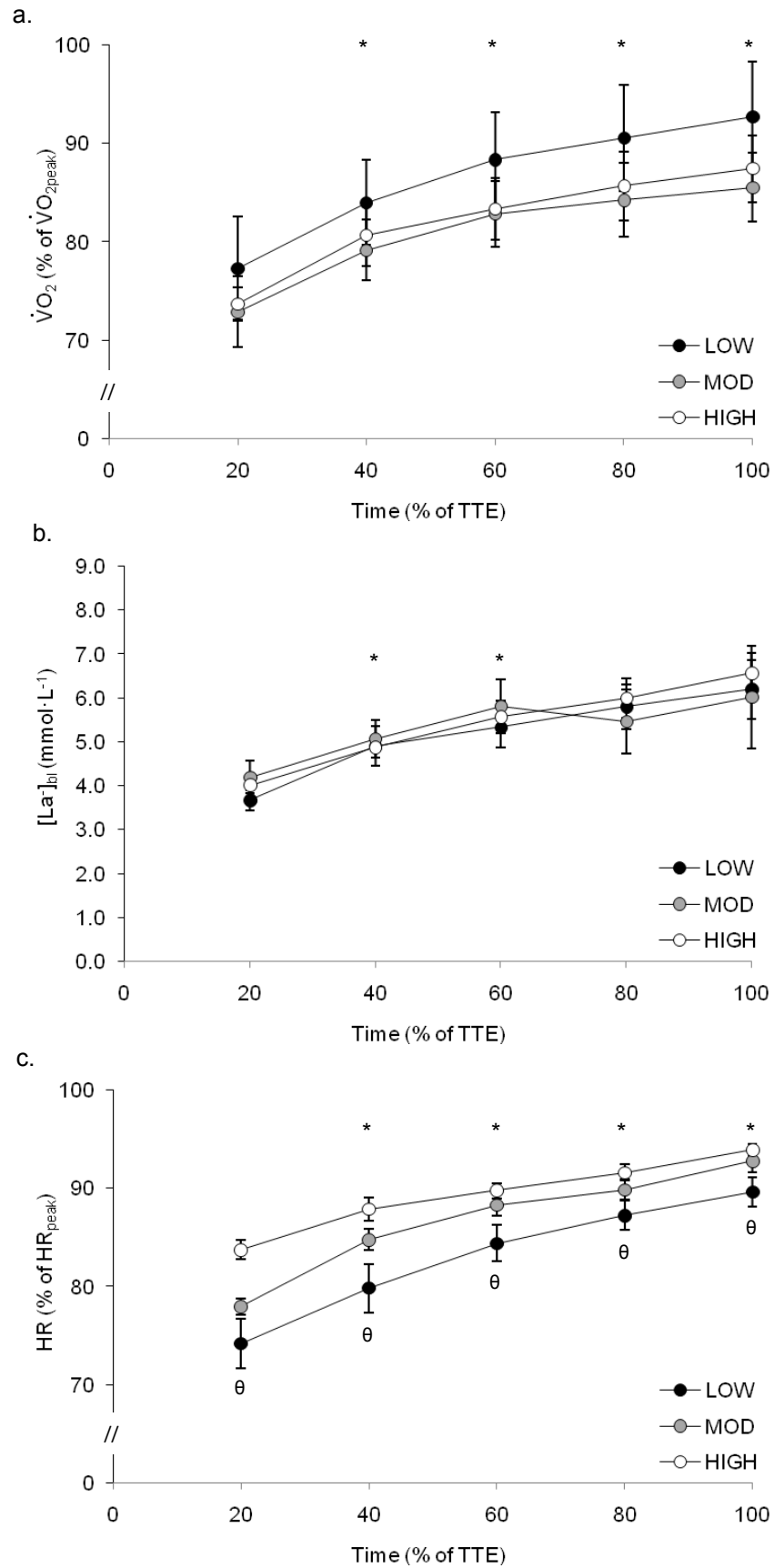
Figure 7.10: a.) $\dot{V}O_2$, b.) blood lactate concentration ($[La^-]_{bl}$) and c.) heart rate (HR) responses to exercise at 95 % of Critical Power
Significantly greater than previous time-point (all groups): * $P < 0.005$; significantly different from HIGH group: [θ] $P < 0.05$

**7.6) Discussion: Part 2 – Responses at and around Critical Power for different fitness groups**

The purpose of part 2 of the present study was to determine the responses to constant-load exercise at 95, 100 and 105 % of CP for groups of differing fitness levels. The results support the experimental hypotheses stated at the end of section 7.1 in part, whereby:

1. The $\dot{V}O_2$ (as a % of $\dot{V}O_{2peak}$) and HR (as a % of $HR_{peak}$) continued to rise during exercise at and above CP for all groups;
2. The $[La^-]_{bl}$ ($mmol \cdot L^{-1}$) attained a steady state during exercise below CP for all groups.

However, contrary to the hypotheses:

1. The $[La^-]_{bl}$ ($mmol \cdot L^{-1}$) did not continue to rise during exercise above CP within the MOD group;
2. The $\dot{V}O_2$ (as a % of $\dot{V}O_{2peak}$) did not attain a delayed steady state during exercise below CP for any of the groups.

*7.6.1) Critical Power determination*

Relative to MMP, the intensities of the exhaustive trials used to determine CP were similar for all three fitness groups (~ 80 – 105 % of MMP, see section 7.3.1). The top end of this range is lower than the highest work rates reported for many studies outlined in table 7.1, whereby the most intense CP determination trials were prescribed at 110 – 129 % of MMP or P-$\dot{V}O_{2max}$ (Baron *et al.*, 2005; Brickley *et al.*, 2002; Carter *et al.*, 2005; Dekerle *et al.*, 2003; McLellan & Cheung, 1992; Pringle & Jones, 2002). Since higher relative work rates of CP determination trials would be expected to elicit shorter exhaustion times and higher CP estimates (Bishop *et al.*, 1998), the responses to exercise at and around CP in the present study should be no more severe than in previous studies. Table 7.5 supports this rationale, whereby the majority of CP estimates from previous studies appear higher than those elicited

within the present study for participants with similar $\dot{V}O_{2peak}$ scores. However, despite higher relative work rates of CP determination trials in the previous studies, exhaustive exercise durations were reportedly similar to the present study, lasting $\sim 2 - 15$ min. This reflects a potential effect of specific trial durations on the CP estimate. For example, exhaustive trials in previous studies may have lasted closer to 2 min than to 15 min (meaning that individual CP estimates were not derived from a series of trials that spanned the full $2 - 15$ min range), which, according to the findings of Bishop *et al.* (1998), would lead to higher CP estimates. Alternatively, the data may suggest a potential difference in aerobic endurance. That is, two individuals with similar absolute $\dot{V}O_{2peak}$ scores may be capable of exercising at different relative work rates over the same time period. While these possibilities were not examined in the present study, the key message is that the CP estimates derived for the LOW, MOD and HIGH groups are not greater than those previously reported for individuals of similar aerobic fitness levels, so the responses to exercise at and around CP should not be any more severe.

*7.6.2) Time to exhaustion at and around Critical Power*

Despite tendencies for the TTE values to be shorter in the HIGH fitness group, there were no significant differences between groups during exercise at 95, 100 or 105 % of CP. This finding was supported by a lack of significant correlations between $\dot{V}O_{2peak}$ and TTE at any of the three exercise intensities (r < 0.31, P > 0.05). Similar results have been reported by Carter *et al.* (2005), who demonstrated no significant correlations between $\dot{V}O_{2max}$ and TTE during exercise at CP. While these findings suggest that TTE during exercise at and around CP does not differ across aerobic fitness groups, a deeper analysis of data performed by Carter *et al.* (2005) showed that individuals who could maintain exercise at CP longer than the group mean duration of $\sim 16$ min tended to have a higher $\dot{V}O_{2max}$ ($\sim 58$ mL·kg$^{-1}$·min$^{-1}$) than those individuals who fatigued more quickly than the group mean duration ($\sim 51$ mL·kg$^{-1}$·min$^{-1}$). Therefore, it seemed that aerobically "fitter" individuals had a greater endurance capacity for cycling at CP. However, this possibility is not supported by data from the current study since those individuals cycling at CP for longer than the group mean duration of 25 min tended to have a lower $\dot{V}O_{2peak}$ (45.7 mL·kg$^{-1}$·min$^{-1}$) than those

individuals who fatigued more quickly than the group mean duration (49.4 mL·kg$^{-1}$·min$^{-1}$). The TTE at CP was also negatively correlated with absolute CP, which further suggests that "fitter" individuals actually fatigue more quickly when cycling at CP. This may be due to the higher relative CP identified in the HIGH versus the LOW group in section 7.3.2, which would indicate that exercise at CP is physiologically more stressful in the HIGH group. This will be discussed in section 7.6.3, while the relationship between CP and TTE is discussed in more detail in chapter 8 with specific reference to the two outlying data points evident in figure 7.7*b*.

Table 7.5: Intensity and duration of Critical Power (CP) determination trials for groups listed according to $\dot{V}O_{2peak}$

| Lead author (year) | $\dot{V}O_{2peak}$ (L·min$^{-1}$) | CP determination trials | | CP (W) |
|---|---|---|---|---|
| | | Relative intensity range (%) | Duration range (min) | |
| *Present study (LOW)* | 2.7 | 78 – 102 $_M$ | 3.6 – 13.0 | 175 |
| Dekerle (2003) | 3.5 | 90 – 110 $_V$ | 3.7 – 13.6 | 278 |
| Baron (2005) | 3.5 | 90 – 110 $_V$ | NR | 284 |
| *Present study (MOD)* | 3.7 | 81 – 106 $_M$ | 3.2 – 12.9 | 211 |
| Pringle (2002) | 3.7 | 50 $_Δ$ – 110 $_V$ | ~ 2 – 15 | 242 |
| McLellan (1992) | 4.1 | 90 – 120 $_V$ | ~ 2 – 15 | 265 |
| Carter (2005) | 4.1 | 90 – 110 $_V$ | 3.6 – 10.7 | 278 |
| *Present study (HIGH)* | 4.4 | 82 – 105 $_M$ | 3.0 – 13.6 | 277 |
| Brickley (2002) | 4.6 | 95 – 120 $_M$ | ~ 1 – 10 | 273 |

Relative to M: maximal minute power; V: $\dot{V}O_{2max}$ ; Δ: $\dot{V}O_{2max}$ minus $\dot{V}O_2$ at lactate threshold
NR = not reported

The greatest differences in mean absolute TTE occurred between the HIGH and MOD fitness groups, with TTE being longer in the MOD group (differences of 10.5, 11.8 and 10.7 min were observed for exercise at 95, 100 and 105 % of CP, respectively). These large differences were non-significant, perhaps due to the wide ranges of exhaustion times recorded within each group. For example, the TTE durations during exercise at CP for the MOD and HIGH groups ranged from 10.3 to 60.0 min (exercise was terminated after 60 min) and 10.2 to 30.5 min, respectively. Such high inter-individual variability in TTE during exercise at CP has been reported previously, whereby exhaustion times between homogenous groups have differed by 11 – 75 min (Brickley *et al.*, 2002; Bull *et al.*, 2000; de Lucas *et al.*, 2002; Scarborough *et al.*,

1991).  The upper boundary to this range (i.e., 75 min) would have been greater still, had the exercise not been terminated by the experimenters after 90 min (Scarborough *et al.*, 1991).  The variation in inter-individual exhaustion times observed within the present study is unlikely to be attributable to a lack of familiarisation, since all participants had completed five TTE tests prior to the first exhaustive trial at, above or below CP.  Moreover, variability in TTE was shown in chapter 6 to remain high during long-duration trials, irrespective of prior familiarisation trials.  While it is possible that low motivation or fatigue may have influenced the results for some individuals, participants were strongly encouraged throughout each test and trials were separated by at least two days in order to minimise the effects of boredom and/or fatigue.  A more detailed investigation of individual TTE responses to exercise at and around CP is included in chapter 8.

*7.6.3) Physiological responses to exercise at Critical Power*

While previous studies have not commonly reported HR attained at the end of exercise at CP as a % of $HR_{peak}$, this physiological measure may be useful in making standardised comparisons both within and between studies.  Results from the present study have shown that end-exercise HR did not differ between fitness groups and values can be expected to exceed 90 % of $HR_{peak}$.  The mean $[La^-]_{bl}$ attained at the end of exercise at CP for the three groups ranged between 7.11 and 8.31 mmol$\cdot$L$^{-1}$.  These values did not differ between groups and are similar to those previously reported in the literature following exercise at CP (see table 7.1).  Moreover, the values are higher than the $[La^-]_{bl}$ levels reported by Baron *et al.* (2008) at the end of exhaustive exercise at MLSS (mean ± SD: 6.18 ± 2.58 mmol$\cdot$L$^{-1}$), thus indicating a significant contribution from anaerobic energy metabolism towards the latter stages of exercise at CP.  The mean $\dot{V}O_2$ attained at the end of exercise at CP ranged between 88 and 97 % of $\dot{V}O_{2peak}$, also similar to previously reported values (table 7.1).  Interestingly, the LOW group, but not the MOD or HIGH groups, attained an end-exercise $\dot{V}O_2$ that was not significantly different from $\dot{V}O_{2peak}$.  This does not appear to be attributable to a larger $\dot{V}O_2$-SC[4] in the LOW group, as values did not differ between the three

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[4] The $\dot{V}O_2$-SC was calculated by subtracting the 5-min $\dot{V}O_2$ from the end-exercise $\dot{V}O_2$ and was expressed as an absolute value in L$\cdot$min$^{-1}$ and as a rate (per minute and per watt) in mL$\cdot$min$^{-2}\cdot$W$^{-1}$.

fitness groups (table 7.6). Instead it is possible that the LOW group experienced a moderate training effect following the numerous exhaustive trials (between five and seven) that were completed prior to the exercise test at 100 % of CP. If this were the case then the high end $\dot{V}O_2$ values expressed as a % of the "original" $\dot{V}O_{2peak}$ would have appeared high for the LOW group. If expressed as a % of the "improved" $\dot{V}O_{2peak}$, the end values would perhaps have been more similar to those of the MOD and HIGH groups. This explanation is strengthened by the values recorded above and below CP for the LOW group, which also exceeded 90 % of, and did not differ from, $\dot{V}O_{2peak}$.

Table 7.6: Mean ± SEM $\dot{V}O_2$-slow component ($\dot{V}O_2$-SC) data for the three fitness groups

| $\dot{V}O_2$-SC | LOW | MOD | HIGH |
|---|---|---|---|
| $L \cdot min^{-1}$ | 0.40 ± 0.04 | 0.47 ± 0.10 | 0.42 ± 0.08 |
| $mL \cdot min^{-2} \cdot W^{-1}$ | 0.17 ± 0.04 | 0.13 ± 0.03 | 0.16 ± 0.03 |

No significant differences between groups: $P > 0.05$

As well as characterising the absolute demands of exercise at CP across a range of fitness groups, one of the main aims of the current study was to investigate the responses over time. The significant increases in $\dot{V}O_2$, $[La^-]_{bl}$ and HR over all consecutive pairs of time-points (i.e., from 20 – 40, 40 – 60, 60 – 80 and 80 – 100 % of TTE) demonstrate that none of the physiological parameters stabilised for any of the groups. A number of previous studies have shown similar responses within homogenous male participants, whereby $\dot{V}O_2$, $[La^-]_{bl}$ and/or HR continued to increase until exhaustion during exercise at CP (Baron *et al.*, 2005; Brickley *et al.*, 2002; McLellan & Cheung, 1992; Overend *et al.*, 1992; Poole *et al.*, 1990). By contrast, however, a selection of studies have previously demonstrated plateaus in $\dot{V}O_2$ and $[La^-]_{bl}$ towards the end of exercise at CP (Baron *et al.*, 2005; Jenkins & Quigley, 1990;1992; Overend *et al.*, 1992; Poole *et al.*, 1988). Figure 7.11 provides a visual comparison of these studies.

Time (min): 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

**$\dot{V}O_2$**

| Study | Pattern | End value |
|---|---|---|
| McLellan (1992) | INCREASE UC | 87 |
| Brickley (2002) | INCREASE * | 91 |
| Baron (2005) | INCREASE * | 90 |
| Baron (2005) | INCREASE * / PLATEAU * | 90 |
| Poole (1990)pt | INCREASE UC | 79 |
| Overend (1992) | PLATEAU * | 85 |
| Poole (1988) | PLATEAU * | 79 |

**$[La^-]_{bl}$**

| Study | Pattern | End value |
|---|---|---|
| McLellan (1993) | INCREASE UC | 6.8 |
| Brickley (2002) | INCREASE * | 6.5 |
| Baron (2005) | INCREASE * | 13.8 |
| Poole (1988) | PLATEAU * | 5.6 |
| Poole (1990)pt | INCREASE UC | 4.2 |
| Overend (1992) | INCREASE * | 8.2 |

**HR**

| Study | Pattern | End value |
|---|---|---|
| Brickley 2002 | INCREASE * | 186 |
| Overend (1992) | INCREASE * | 182 |

| Study | Pattern | End value |
|---|---|---|
| $\dot{V}O_2$ Jenkins (1992)pt | PLATEAU * | 77 |
| $[La^-]_{bl}$ Jenkins (1992)pt | PLATEAU * | 10.8 |
| $[La^-]_{bl}$ Jenkins (1990) | PLATEAU UC | 8.9 |

Figure 7.11: Increases and plateaus in $\dot{V}O_2$, blood lactate concentration ($[La^-]_{bl}$) and heart rate (HR) reported over time during exercise at Critical Power

Studies (lead author, year) are ordered according to exercise time, then by duration of plateau. End-exercise values are labelled at the end of each block for $\dot{V}O_2$ (% of $\dot{V}O_{2max}$), $[La^-]_{bl}$ (mmol·L$^{-1}$) and HR (beats·min$^{-1}$)

pt: post training data; UC: statistical significance unclear; * P < 0.05

The Jenkins studies have been listed separately since exercise intensity was slightly lower than Critical Power

The majority of authors have concluded that exercise at CP reflects a non-steady state and, despite the reported plateaus, the two studies by Jenkins and Quigley (1990; 1992) would support this conclusion. That is, in both of their studies, which imposed either 30 or 40 min of exercise at CP, the exercise intensity had to be reduced below CP (by ~ 11 – 14 W, or 5 – 6 %) in order for the participants to complete the full exercise duration. The plateaus in $\dot{V}O_2$ and [La$^-$]$_{bl}$ observed by Poole et al. (1988) and Overend et al. (1992) may be due to the short consecutive time periods over which these authors analysed their data (i.e., 2 – 4 min). This implies that different approaches to reporting data would have a significant impact upon whether CP is thought to reflect a steady or a non-steady state. This observation is supported by the results of Baron et al. (2005), who showed a plateau in $\dot{V}O_2$ from 50 – 100 % of TTE (equivalent to ~ 11 min) but an increase in $\dot{V}O_2$ from 3 min to the end of exercise (equivalent to ~ 19 min) using the same data set. It may be concluded that the results from the current study are consistent with the majority of previous research in associating a physiological non-steady state with exercise at CP. However, it is clear from previous and present data that there is a need to standardise the method of reporting physiological responses to exercise at CP, in order that comparisons may be made between studies.

The current study expressed physiological data over time relative to TTE, rather than at absolute time points, which allows data to be grouped when participants fatigue after varying durations. This method of tracking changes in 20 % increments has been used previously in a CP study with children (Williams *et al.*, 2008). Although Williams et al. (2008) reported a physiological non-steady state during exercise at CP (with boys aged 12.7 ± 0.3 y), data were not analysed statistically over consecutive time points. The present study is the first to show that exercise at CP elicits significant increases in $\dot{V}O_2$ , [La$^-$]$_{bl}$ and HR over time increments expressed as 20 % of TTE.

*7.6.4) Physiological responses to exercise above Critical Power*

The end-exercise $\dot{V}O_2$ , [La$^-$]$_{bl}$ and HR values following exercise at 105 % of CP did not differ from those attained at the end of exercise at CP for any of the three fitness

groups. This was despite shorter exhaustion times for the MOD and HIGH groups at 105 (compared with 100) % of CP. Therefore, the physiological limits to exercise at and above CP would appear to be similar, but are reached at a faster rate during exercise above CP. This implies that exercise at 100 and 105 % of CP lie within the same exercise-intensity domain. However, the specific exercise-intensity domain may differ with aerobic fitness as the maximal $\dot{V}O_2$ attained for the LOW group did not differ from $\dot{V}O_{2peak}$, whereas for the MOD and HIGH groups it occurred below $\dot{V}O_{2peak}$ (at ~ 85 − 90 %). These findings differ from previous studies, which have found $\dot{V}O_2$ to increase up to $\dot{V}O_{2max}$ during exercise at ~ 105 % of CP within healthy, active individuals (Hill *et al.*, 2002; Poole *et al.*, 1988; Poole *et al.*, 1990). These physiological discrepancies may be explained by participants used by Poole *et al.* (1988; 1990), who had unusually low average CP scores given their $\dot{V}O_{2max}$ characteristics. This can be seen in table 7.1, whereby average CP scores of 197 W and 217 W are considerably lower than the CP scores for other participant groups with similar $\dot{V}O_{2max}$ scores. Lower relative CP values would result in reduced physiological stress during exercise at CP, which may explain the stable $\dot{V}O_2$ responses to exercise at CP.

In agreement with the hypotheses and consistent with the responses to exercise at CP, the present study identified increases over time in $\dot{V}O_2$ and HR until exhaustion for all groups. This was also the case for [La⁻]$_{bl}$ within the LOW and HIGH groups. However, failing to support the second hypothesis and in contrast to the responses to exercise at CP, [La⁻]$_{bl}$ did not increase significantly within the MOD group beyond 60 % of TTE. This result was unexpected and does not appear to be explained by higher resting [La⁻]$_{bl}$ values within the MOD group, since these were similar for all groups (1.4 ± 0.3, 1.5 ± 0.1 and 1.1 ± 0.1 mmol·L$^{-1}$ for LOW, MOD and HIGH groups, respectively). A closer inspection of individual data may explain the factors involved in eliciting a statistical plateau. Firstly, one participant experienced a drop in [La⁻]$_{bl}$ after 60 % of TTE (i.e., beyond 35 min) and [La⁻]$_{bl}$ then remained suppressed until the end of exercise, which was enforced after 60 min. Since this participant was not fatigued after 60 min of exercise at 105 % of CP it is probable that the exercise intensity was sufficiently low to allow for oxidation of prior La⁻ accumulation in the muscles, thus resulting in a drop in [La⁻]$_{bl}$ during the exercise bout. However, it

remains unclear why this drop in [La$^-$]$_{bl}$ would occur after 35 min of constant-load exercise. Secondly, another participant within the MOD group elicited a lower final [La$^-$]$_{bl}$ value compared with the values recorded at 40, 60 and 80 % of TTE. Since this particular individual was exhausted after 20.1 min, this reduction in [La$^-$]$_{bl}$ at 100 % of TTE is more likely due to measurement error than lactate oxidation, as there would be no reason for a reduction in lactate accumulation at the end of an exhaustive 20-min, constant-load exercise bout. Finally, the MOD group demonstrated higher variation around all mean [La$^-$]$_{bl}$ values compared with the LOW and HIGH groups, which would reduce the likelihood of identifying a significant difference from one time point to the next. Indeed, additional statistical analyses without the two outlying subjects described here showed [La$^-$]$_{bl}$ to differ significantly in the MOD group between each consecutive time-point ($P < 0.05$). On reflection, since 6 of the 8 participants within the MOD group experienced a continuous rise in [La$^-$]$_{bl}$, and since the LOW and HIGH groups experienced significant increases over all time points, [La$^-$]$_{bl}$, as well as $\dot{V}O_2$ and HR, is likely to be unstable during exercise above CP in almost all cases.

*7.6.5) Physiological responses to exercise below Critical Power*

As outlined in section 3.3.4, no previous research has directly compared the responses to exercise at and below CP, although comparisons between MLSS and CP suggest that exercising slightly below CP may elicit a steady state in [La$^-$]$_{bl}$ (Dekerle *et al.*, 2003; Pringle & Jones, 2002). Results from the current study may be interpreted to support this theory, since there was no change in [La$^-$]$_{bl}$ after 60 % of TTE for any of the groups during exercise at 95 % of CP. However, MLSS has been specifically defined as a change in [La$^-$]$_{bl}$ of $\leq 1$ mmol·L$^{-1}$ within the last 20 min of constant-load exercise (Beneke, 1995). Based on this definition, results from the current study would suggest that exercise at 95 % of CP exceeds MLSS for the LOW and HIGH groups, since the mean ± SEM change in [La$^-$]$_{bl}$ in the last 20 min of exercise was 1.26 ± 0.75 and 1.68 ± 0.28 mmol·L$^{-1}$, respectively. However, the mean change in [La$^-$]$_{bl}$ was only 0.79 ± 0.70 mmol·L$^{-1}$ for the MOD group, implying that 95 % of CP is lower than or equal to MLSS within this population. The large inter-individual variation in [La$^-$]$_{bl}$ responses must be acknowledged when drawing these conclusions,

though. For example, the changes in $[La^-]_{bl}$ in the last 20 min of exercise at 95 % of CP ranged from -1.13 to 5.05, -1.16 to 5.15 and 0.63 to 2.94 mmol·L$^{-1}$ for the LOW, MOD and HIGH groups, respectively.

Unlike $[La^-]_{bl}$, both $\dot{V}O_2$ and HR increased over all consecutive time points for all groups during exercise below CP and end-exercise values did not differ from those attained during exercise at or above CP. These findings indicate that exercise at 95 % of CP lies beyond the heavy-intensity exercise domain in most cases. With TTE systematically longer during exercise below CP, the main difference is that the physiological limits are reached at a slower rate compared with exercise at and above CP.

*7.6.6) Summary*

Part 2 of the current study has identified that TTE, $\dot{V}O_2$, $[La^-]_{bl}$ and HR responses are not significantly different across fitness groups during exercise at CP. Furthermore, these responses remain largely similar between fitness groups during exercise above and below CP. When investigating the physiological responses to exercise at and around CP over time, $\dot{V}O_2$ and HR did not attain a steady state during exercise below, at or above CP for any of the fitness groups. In addition, $[La^-]_{bl}$ was unable to stabilise during exercise at and above CP for all fitness groups. In conclusion, results from the present study do not support recent publications (Burnley *et al.*, 2006; Jones *et al.*, 2010; Jones *et al.*, 2009; Jones *et al.*, 2008; Smith & Jones, 2001; Vanhatalo *et al.*, 2007) that describe CP as a parameter that reflects MLSS, a stabilisation of $\dot{V}O_2$ over time, the boundary between the heavy and severe exercise-intensity domains or the highest work rate above which $\dot{V}O_{2max}$ is attained. Instead, exercise at CP leads to a physiologically unstable environment that results in fatigue within around 10 – 40 min, probably due to a combination of inexorable increases in $\dot{V}O_2$, $[La^-]_{bl}$ and HR over time.

While $\dot{V}O_{2peak}$ was used in the present study to differentiate aerobic fitness groups, as has been the procedure in previous experimental studies (Baldwin *et al.*, 2000; Proctor *et al.*, 1995; Tomlin & Wenger, 2002), this grouping method is potentially limited

since aerobic fitness is dependent upon numerous other factors (i.e., LT, economy or efficiency and $\dot{V}O_2$ kinetics). An alternative grouping method will be examined in greater detail in chapter 8. Since the current chapter has highlighted the validity of CP as a marker of aerobic fitness that is closely related to both LT and $\dot{V}O_{2peak}$, aerobic fitness parameters may be equally or better differentiated by grouping according to CP, rather than $\dot{V}O_{2peak}$.

# 8) A Post-Experimental Analysis of Chapter 7

While the results and discussion sections within the previous chapter fulfilled the aims outlined in section 7.1, the data produced a number of interesting and unexpected results. These results led to several further research questions that were beyond the scope of the original aims of chapter 7. Therefore, the initial objective of the current chapter is to approach these supplementary questions as short, discrete, research problems. Two main themes have been developed and will be addressed within sections 8.1 and 8.2, respectively: (i) to investigate more closely the method of grouping for fitness according to $\dot{V}O_{2peak}$, and (ii) to investigate more closely individual TTE responses to exercise at CP. A second objective of the current chapter, which will be addressed in section 8.3, is to use the data collected for chapter 7 to investigate more closely the CP modelling process and the practical applications of CP modelling.

## 8.1) Limitations of grouping for fitness by $\dot{V}O_{2peak}$

### 8.1.1) Rationale

A number of unexpected results were reported in table 7.3, whereby power output-, $\dot{V}O_2$ - and $\Delta$-related parameters did not necessarily differ between all fitness groups, despite significant differences in $\dot{V}O_{2peak}$. Since LT has been identified as a marker of aerobic fitness, P-LT and $\dot{V}O_2$-LT may have been expected to differ between all three groups. However, no differences were identified between the LOW and MOD groups, suggesting that $\dot{V}O_{2peak}$ alone was not able to distinguish aerobic fitness. The lack of differences between the LOW and MOD groups may have been due to the smaller differences in $\dot{V}O_{2peak}$ between the two groups (compared with the MOD and HIGH groups). For example, the "most fit" LOW group participant and the "least fit" MOD group participant elicited $\dot{V}O_{2peak}$ values of 40.6 and 43.6 mL·kg$^{-1}$·min$^{-1}$, respectively (i.e., a difference of only 3.0 mL·kg$^{-1}$·min$^{-1}$, or ~ 7 %). Since an individual's $\dot{V}O_{2max}$ has been shown to vary, 98 % of the time, within a range of ± 11 % (Katch *et al.*, 1982), it is possible that some participants in the LOW and MOD

groups may, on another testing day, have been categorised into the alternate group. By contrast, the "most fit" MOD group participant and the "least fit" HIGH group participant elicited $\dot{V}O_{2peak}$ values of 49.6 and 57.8 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively (i.e., a difference of 8.2 $mL \cdot kg^{-1} \cdot min^{-1}$, or ~ 15 %). This larger differentiation between the MOD and HIGH groups probably explains why the HIGH group elicited significant differences from the LOW and MOD groups for many of the LT- and CP-related parameters.

It was confirmed in section 7.4 that CP is a valid marker of aerobic fitness, based on the findings that: (i) CP relates similarly to the exercise-intensity domain continuum, irrespective of $\dot{V}O_{2peak}$ group, and (ii) strong correlations exist between CP and $\dot{V}O_2$ - LT, P-LT and $\dot{V}O_{2peak}$. However, with changes in CP not directly linked with changes in $\dot{V}O_{2peak}$, the data in chapter 7 suggest that the two parameters contribute somewhat independently to aerobic fitness, with CP perhaps exhibiting endurance-like characteristics. To investigate further the potential limitations of close $\dot{V}O_{2peak}$ groupings, and to examine the nature of CP as a valid marker of aerobic fitness and aerobic endurance, the aim of the present section is to re-analyse the data reported in section 7.3 by:

1. Re-grouping participants into two groups of n = 8 ([2 x n=8]) using the bottom and top eight participants ranked according to $\dot{V}O_{2peak}$ (thereby creating larger between-group differences in $\dot{V}O_{2peak}$)
2. Re-grouping participants according to CP (W) and replicating the analyses carried out on the $\dot{V}O_{2peak}$ -ranked groups.

It is hypothesised that:

1. The [2 x n=8] re-grouping according to $\dot{V}O_{2peak}$ will result in significant differences in P-LT and CP (measured in W) and $\dot{V}O_2$ -LT (measured in $mL \cdot kg^{-1} \cdot min^{-1}$) between the groups;
2. Re-grouping according to CP will elicit group differences that are not evident when grouping according to $\dot{V}O_{2peak}$.

T-tests with Bonferroni adjustments were used to compare group differences for the two groups of n = 8. Results for the [2 x n=8] $\dot{V}O_{2peak}$ and CP re-grouping systems are displayed in tables 8.1 and 8.2, respectively. The LOW group reflects the bottom eight ranked participants and the HIGH group reflects the top eight ranked participants. The relationships between the $\dot{V}O_2$-related parameters for the LOW and HIGH groups (similar to those presented in figure 7.6) are displayed in figures 8.1 and 8.2 for the $\dot{V}O_{2peak}$ and CP re-grouping systems, respectively.

Table 8.1: Descriptive (mean ± SD) and comparative (mean ± SEM) data for $\dot{V}O_{2peak}$ groups

| | | LOW | HIGH |
|---|---|---|---|
| Descriptive | Age (y) | $32.1 \pm 4.9$ | $32.4 \pm 8.8$ |
| | Body mass (kg) | $80.0 \pm 12.1$ | $69.3 \pm 7.9$ |
| Power output (W) | P-LT | $116 \pm 14^{**}$ | $191 \pm 9$ |
| | CP | $176 \pm 11^{**}$ | $277 \pm 17$ |
| | MMP | $255 \pm 14^{**}$ | $358 \pm 17$ |
| Power output (% of MMP) | P-LT | $45 \pm 5$ | $54 \pm 2$ |
| | CP | $69 \pm 2^{*}$ | $77 \pm 2$ |
| $\dot{V}O_2$ (mL·kg$^{-1}$·min$^{-1}$) | $\dot{V}O_2$-LT | $17.2 \pm 1.3^{**}$ | $35.1 \pm 1.8$ |
| | $\dot{V}O_2$-CP$_{est}$ | $23.9 \pm 1.3^{**}$ | $51.0 \pm 1.4$ |
| | $\dot{V}O_{2peak}$ | $34.1 \pm 1.4^{**}$ | $63.6 \pm 1.4$ |
| $\dot{V}O_2$ (% of $\dot{V}O_{2peak}$) | $\dot{V}O_2$-LT | $50 \pm 2$ | $55 \pm 2$ |
| | $\dot{V}O_2$-CP$_{est}$ | $70 \pm 3^{*}$ | $80 \pm 2$ |
| $\Delta$ (mL·kg$^{-1}$·min$^{-1}$) | $\dot{V}O_{2peak} - \dot{V}O_2$-LT | $16.9 \pm 0.7^{**}$ | $28.5 \pm 1.3$ |
| $\dot{V}O_2$ (% of $\Delta$) | $\dot{V}O_2$-CP$_{est}$ | $39 \pm 7$ | $55 \pm 5$ |

Significantly different from HIGH: * P<0.05, ** P<0.001

Table 8.2: Descriptive (mean $\pm$ SD) and comparative (mean $\pm$ SEM) data for CP groups

| | | LOW | HIGH |
|---|---|---|---|
| Descriptive | Age (y) | $32.9 \pm 5.3$ | $32.5 \pm 8.9$ |
| | Body mass (kg) | $79.5 \pm 11.4$ | $74.7 \pm 12.3$ |
| Power output (W) | P-LT | $97 \pm 10**$ | $188 \pm 9$ |
| | CP | $165 \pm 9**$ | $280 \pm 15$ |
| | MMP | $243 \pm 10**$ | $364 \pm 15$ |
| Power output (% of MMP) | **P-LT** | **$40 \pm 4*$** | **$51 \pm 2$** |
| | CP | $68 \pm 2*$ | $77 \pm 2$ |
| $\dot{V}O_2$ (mL·kg$^{-1}$·min$^{-1}$) | $\dot{V}O_2$ -LT | $16.7 \pm 1.3**$ | $33.5 \pm 2.2$ |
| | $\dot{V}O_2$ -CP$_{est}$ | $26.1 \pm 2.00**$ | $49.7 \pm 2.6$ |
| | $\dot{V}O_{2peak}$ | $37.1 \pm 2.3**$ | $61.9 \pm 2.5$ |
| $\dot{V}O_2$ (% of $\dot{V}O_{2peak}$) | **$\dot{V}O_2$ -LT** | **$45 \pm 3*$** | **$54 \pm 2$** |
| | $\dot{V}O_2$ -CP$_{est}$ | $70 \pm 2*$ | $80 \pm 2$ |
| $\Delta$ (mL·kg$^{-1}$·min$^{-1}$) | $\dot{V}O_{2peak}$ $-$ $\dot{V}O_2$ -LT | $20.4 \pm 1.8*$ | $28.4 \pm 1.4$ |
| $\dot{V}O_2$ (% of $\Delta$) | $\dot{V}O_2$ -CP$_{est}$ | $44 \pm 7$ | $56 \pm 5$ |

Significantly different from HIGH: * $P < 0.05$, ** $P < 0.001$ (significant differences evident in table 8.2 but not in table 8.1 are highlighted in **bold**)

a.

$\dot{V}O_2$-LT $\quad\quad$ $\dot{V}O_2$-CP$_{est}$ $\quad$ $\dot{V}O_{2peak}$

▲--------------------●--------------------◆ HIGH

△--------●--------◇ LOW

0 $\quad$ 10 $\quad$ 20 $\quad$ 30 $\quad$ 40 $\quad$ 50 $\quad$ 60 $\quad$ 70

$\dot{V}O_2$ (mL·kg$^{-1}$·min$^{-1}$)

b.

$\dot{V}O_2$-LT $\quad\quad\quad\quad$ $\dot{V}O_2$-CP$_{est}$ $\quad\quad$ $\dot{V}O_{2peak}$

△----------------------●----------------------◇ HIGH

△----------------------●----------------------◇ LOW

0 // 40 $\quad$ 50 $\quad$ 60 $\quad$ 70 $\quad$ 80 $\quad$ 90 $\quad$ 100
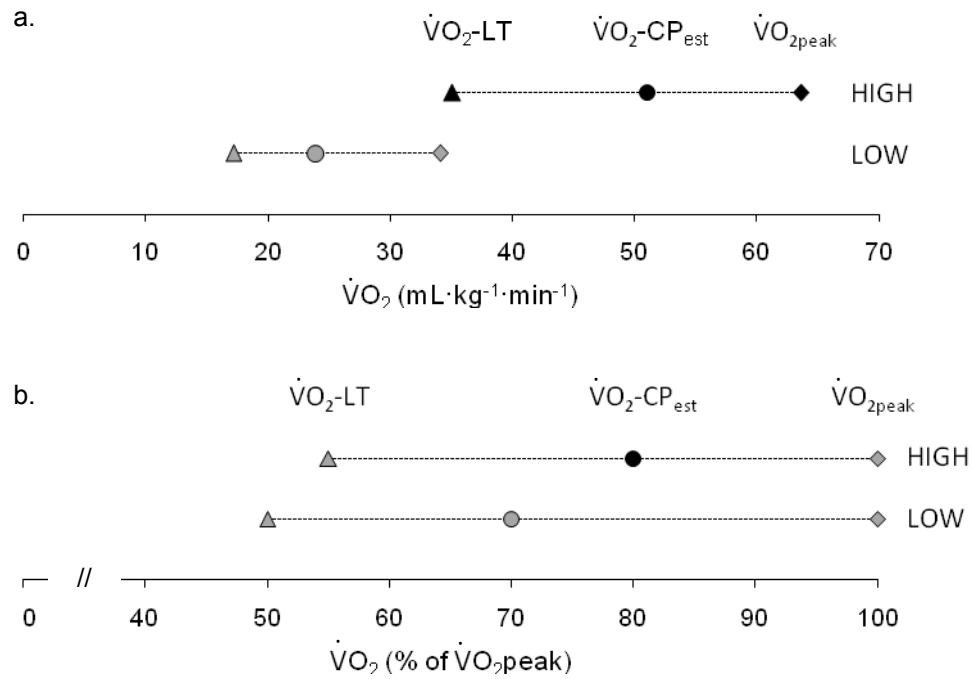
$\dot{V}O_2$ (% of $\dot{V}O_2$peak)

Figure 8.1: Relationships between $\dot{V}O_2$ at lactate threshold ($\dot{V}O_2$-LT), estimated $\dot{V}O_2$ at Critical Power ($\dot{V}O_2$-CP$_{est}$) and $\dot{V}O_{2peak}$ expressed a.) in mL·kg$^{-1}$·min$^{-1}$, and b.) as a % of $\dot{V}O_{2peak}$ for the LOW and HIGH $\dot{V}O_{2peak}$ groups (black fill: significantly different from LOW)

a.

$\dot{V}O_2$-LT $\quad\quad$ $\dot{V}O_2$-CP$_{est}$ $\quad$ $\dot{V}O_{2peak}$

▲--------------------●--------------------◆ HIGH

△----------●----------◇ LOW

0 $\quad$ 10 $\quad$ 20 $\quad$ 30 $\quad$ 40 $\quad$ 50 $\quad$ 60 $\quad$ 70

$\dot{V}O_2$ (mL·kg$^{-1}$·min$^{-1}$)

b.

$\dot{V}O_2$-LT $\quad\quad\quad\quad$ $\dot{V}O_2$-CP$_{est}$ $\quad\quad$ $\dot{V}O_{2peak}$

▲----------------------●----------------------◇ HIGH

△----------------------●----------------------◇ LOW

0 // 40 $\quad$ 50 $\quad$ 60 $\quad$ 70 $\quad$ 80 $\quad$ 90 $\quad$ 100
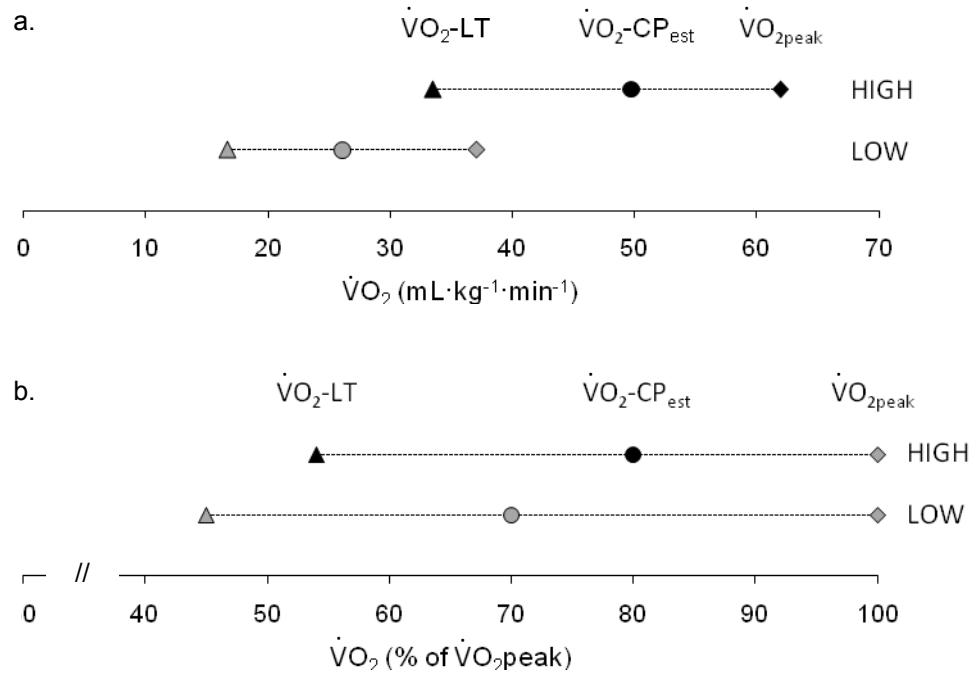
$\dot{V}O_2$ (% of $\dot{V}O_2$peak)

Figure 8.2: Relationships between $\dot{V}O_2$ at lactate threshold ($\dot{V}O_2$-LT), estimated $\dot{V}O_2$ at Critical Power ($\dot{V}O_2$-CP$_{est}$) and $\dot{V}O_{2peak}$ expressed a.) in mL·kg$^{-1}$·min$^{-1}$, and b.) as a % of $\dot{V}O_{2peak}$ for the LOW and HIGH CP groups (black fill: significantly different from LOW)

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*8.1.3) Commentary*

The primary objective of these analyses was to further investigate why some of the power output-, $\dot{V}O_2$- and Δ-related parameters reported in table 7.3 did not differ between all fitness groups, despite significant differences in $\dot{V}O_{2peak}$. A secondary aim was to investigate the validity of CP as a marker of aerobic fitness and aerobic endurance by grouping individuals according to CP. The first hypothesis stated in section 8.1.1 was supported, whereby the system of re-grouping to [2 x n=8] for individuals ranked by $\dot{V}O_{2peak}$ showed that all absolute measures of power output, $\dot{V}O_2$ and Δ were different between the LOW and HIGH groups (table 8.1). Since this was not the case for the LOW, MOD and HIGH groups in chapter 7, it appears that more extreme $\dot{V}O_{2peak}$ groupings are required for differences to be detected in P-LT, CP and MMP (measured in W) and $\dot{V}O_2$-LT and Δ (measured in $mL \cdot kg^{-1} \cdot min^{-1}$). These observations suggest that LT, CP and MMP parameters are subtly different from $\dot{V}O_{2peak}$ in their physiological characteristics, perhaps more closely related to peripheral factors such as muscle capillary density, glycogen utilisation, $La^-$ production and percentage of type I muscle fibres, as these have previously been associated with sustaining high-intensity, constant-load exercise (Coyle *et al.*, 1988).

Consistent with the results in chapter 7, P-LT as a % of MMP and $\dot{V}O_2$-LT as a % of $\dot{V}O_{2peak}$ (i.e., the relative LT parameters) were not significantly different between the LOW and HIGH groups (table 8.1). This supports the explanation provided in section 7.4 that relative LT does not increase as $\dot{V}O_{2peak}$ increases, due to concomitant increases in absolute LT and $\dot{V}O_{2peak}$. This may also explain the non-significant difference in $\dot{V}O_2$-$CP_{est}$ as a % of Δ, as Δ incorporates both $\dot{V}O_2$-LT and $\dot{V}O_{2peak}$ (i.e., Δ = $\dot{V}O_{2peak}$ − $\dot{V}O_2$-LT). By contrast, when re-grouped according to CP the HIGH group elicited higher relative P-LT and relative $\dot{V}O_2$-LT values compared with the LOW group (shown in bold on table 8.2). This suggests that absolute CP may be able to differentiate for aerobic endurance (i.e., relative LT), while $\dot{V}O_{2peak}$ is not. The difference in relative $\dot{V}O_2$-LT between groups highlighted in figure 8.2 reflects a greater shift in $\dot{V}O_2$-LT relative to $\dot{V}O_{2peak}$ as CP increases. This supports the notion

of a closer link between LT and CP than LT and $\dot{V}O_{2peak}$, perhaps due to common endurance-like characteristics.

With reference to the second hypothesis, grouping according to CP is able to differentiate between LT, CP and $\dot{V}O_{2peak}$-based parameters perhaps more completely than grouping according to $\dot{V}O_{2peak}$. Although speculative, with CP lying between LT and $\dot{V}O_{2peak}$ on a theoretical exercise-intensity continuum, it may be that the specific physiological adaptations associated with increases in CP comprise a combination of the factors associated with increases in LT and $\dot{V}O_{2peak}$. This may explain why relative CP and relative $\dot{V}O_2$-CP$_{est}$ were significantly higher in the HIGH group compared with the LOW group in both grouping systems, while relative LT parameters were not. That is, CP increases to a greater extent than $\dot{V}O_{2peak}$ when aerobic fitness is grouped according to both CP and $\dot{V}O_{2peak}$, implying an enhanced combined effect of peripheral and central adaptations on CP.

*8.1.4) A summary of the re-grouping systems*

The current section has shown that extreme $\dot{V}O_{2peak}$ categorisations (i.e., all individuals < 40 and > 57 mL·kg$^{-1}$·min$^{-1}$ in the LOW and HIGH groups, respectively) led to group distinctions in all absolute measures of aerobic fitness, but not in the relative measures of LT (which may reflect aerobic endurance). This was presumably due to concurrent increases in LT and the associated maximal parameters. By contrast, relative CP was differentiated by changes in $\dot{V}O_{2peak}$ and may, therefore, be considered a valid marker of aerobic fitness, as well as endurance. In addition, re-grouping according to CP revealed differences in relative LT while grouping according to $\dot{V}O_{2peak}$ did not. This may imply a common link between LT and CP, with both potential markers of aerobic endurance limited by peripheral muscle adaptations. In conclusion, it is fair to suggest that CP-related parameters have been supported as valid markers of aerobic fitness. More specific research is required to identify the validity of relative CP as a marker of aerobic endurance, as well as the mechanisms underlying independent shifts in LT-, CP- and $\dot{V}O_{2peak}$- related parameters.

**8.2) Explaining time to exhaustion at Critical Power**

*8.2.1) Rationale*

Time to exhaustion during exercise at CP has been reported in a number of studies and inter-individual exercise durations are highly variable. However, despite studies focusing on responses to exercise at CP, the variable TTE response is not well understood. In section 7.5.1, TTE at CP was compared for LOW, MOD and HIGH fitness groups and while the HIGH group tended to exhaust more quickly than the LOW and MOD groups, there were no significant differences between groups. This may have been due to: (i) highly variable TTE data that masked a significant difference between TTE at CP for fitness groups, or (ii) no significant differences existing between TTE at CP for fitness groups.

The first possibility is supported by the high inter-individual variability observed within each of the three groups. For example, the ranges of exhaustion times during exercise at CP for the LOW, MOD and HIGH groups were 13.2 – 53.2 min, 10.3 – 60.0 min and 10.2 – 30.5 min, respectively (the upper boundary for the MOD group would have been higher if exercise at CP had not been terminated at 60 min). It is reasoned, therefore, that less variability within each group may have resulted in significant group differences. Alternatively, rather than high variability masking an inverse relationship between fitness and TTE, it may be that outlying data points for the LOW and MOD groups skewed the data and implied a tendency for TTE at CP to be greater in the lower fitness groups when, in fact, there is no difference. This theory is supported by the non-significant relationship between $\dot{V}O_{2peak}$ and TTE that was reported in section 7.5.1.

Given these possibilities, which were originally highlighted in section 7.6.1, the objective of the current section is to better understand the TTE response to exercise at CP. The specific aims are three-fold:

1. To re-group participants according to the two systems introduced in section 8.1 (i.e., [2 x n=8] and ranking by CP) in order to examine the TTE responses to exercise at CP between the re-defined fitness groups;

2. To re-analyse the group data after removing the two outlying data points in the LOW and MOD groups, which identify two individuals who cycled for considerably longer than all other participants during exercise at CP;

3. To investigate the variable TTE response to exercise at CP using a case-study approach, comparing pairs of individuals with very different TTE results.

*8.2.2) Time to exhaustion using re-grouped data*

In chapter 7 participants were divided into LOW (n = 9), MOD (n = 8) and HIGH (n = 8) fitness groups based on their $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$). In section 8.1 participants were re-grouped into two groups of eight ([2 x n=8]), again based on their $\dot{V}O_{2peak}$. This was to create more discrete fitness bands. Individuals were also re-grouped according to their CP, to determine whether CP could be used as a valid measure for distinguishing fitness groups. In the current analyses both of these re-grouping systems will be used to compare TTE responses to exercise at CP between fitness groups. An additional grouping system has been added, whereby all 25 participants were ranked according to CP and grouped as LOW (n = 9), MOD (n = 8) and HIGH (n = 8). This was to directly compare the original $\dot{V}O_{2peak}$-ranked groups identified in chapter 7 with CP-ranked groups, and was included to support the previous data that have shown CP and $\dot{V}O_{2peak}$ to reflect different physical capacities. The results are displayed in table 8.3.

Table 8.3: Mean ± SEM time to exhaustion (TTE) in min at Critical Power (CP) for groups based on $\dot{V}O_{2peak}$ and CP rankings

| | | n | TTE (min) | P value |
|---|---|---|---|---|
| $\dot{V}O_{2peak}$ rankings (n = 25) | LOW | 9 | 26.5 ± 4.2 | |
| | MOD | 8 | 30.0 ± 5.1 | 0.149 |
| | HIGH | 8 | 18.2 ± 2.7 | |
| CP rankings (n = 25) | LOW | 9 | 31.8 ± 5.4 | |
| | MOD | 8 | 23.2 ± 2.7 | 0.093 |
| | HIGH | 8 | 19.1 ± 3.0 | |
| $\dot{V}O_{2peak}$ rankings ([2 x n=8]) | LOW | 8 | 23.2 ± 2.8 | 0.225 |
| | HIGH | 8 | 18.2 ± 2.7 | |
| CP rankings ([2 x n=8]) | **LOW** | **8** | **34.1 ± 5.5\*** | 0.031 |
| | HIGH | 8 | 19.1 ± 3.0 | |

Significantly different from HIGH: * P < 0.05 (significant differences evident in CP- but not in $\dot{V}O_{2peak}$ -based rankings are highlighted in **bold**)

The data in table 8.3 show that TTE at CP does not get progressively shorter for the three $\dot{V}O_{2peak}$ groups. This is clear from the original LOW, MOD and HIGH groupings, whereby the LOW group were exhausted after 26.5 ± 4.2 min, the MOD group in an increased time of 30.0 ± 5.1 min and the HIGH group in a shorter time again of 18.2 ± 2.7 min (as shown in figure 7.5). Similarly, the more extreme [2 x n=8] $\dot{V}O_{2peak}$ groupings still did not elicit significant differences in TTE at CP (P = 0.225). By contrast, the three groups classified according to CP showed a tendency for individuals with a lower CP to cycle for longer at CP than those with a higher CP and the comparison for the [2 x n=8] groups ranked by CP confirms this relationship, with the LOW group exercising for significantly longer (by ~ 15 min) than the HIGH group (P = 0.031). These results support the negative correlation illustrated in figure 7.7 and suggest that tolerance to exercise at CP may be related to the absolute exercise intensity. This observation, coupled with the higher $\dot{V}O_2$ -CP$_{est}$ as a % of $\dot{V}O_{2peak}$ in the HIGH CP group (shown in table 8.2), implies that HIGH CP individuals may be working in a more intense exercise domain during exercise at CP compared with LOW CP individuals. However, this is inconsistent with the previous suggestion that CP relates similarly to the exercise-intensity domains, irrespective of $\dot{V}O_{2peak}$ , and perhaps the claim in section 7.1 that the absolute value of CP does not appear to relate

to whether exercise at CP elicits a steady or a non-steady state. It is speculated that there are different dominant fatigue mechanisms during exercise at CP for the two groups. That is, the contribution of various factors to exhaustion (i.e., locomotive, respiratory and other peripheral muscle fatigue; muscle perfusion; regulation of fuel, metabolite and ionic homeostasis; central nervous system) is likely to have been different for the HIGH group after $19.1 \pm 3.0$ min compared with the LOW group after $34.1 \pm 5.5$ min. However, given the highly complex and integrative nature of fatigue (McKenna & Hargreaves, 2008), the specific mechanisms separating these two groups is unknown. Whether higher absolute power outputs augment physiological stress (i.e., $\dot{V}O_2$, $[La^-]_{bl}$ and HR) in the HIGH group more than the LOW group will be investigated in more detail in section 8.2.4.

*8.2.3) Re-analysis following the removal of outlying data points*

As suggested in the rationale for the current analyses, it is possible that outlying data points are skewing the relationship between fitness and TTE. For example, it can be seen in figure 7.7 (section 7.5.1) that two individuals, one in the LOW group and one in the MOD group, cycled for considerably longer than all other participants during exercise at CP (i.e., 53.2 and 60.0 min, versus $10.3 - 35.6$ min for all other participants). It should be restated that the exercise was capped at 60 min, so the second outlying value would have been higher still if cycling was permitted to continue. Given these observations, the following questions are raised: if the outliers are removed, (i) is there still a tendency for TTE to be longer in the HIGH $\dot{V}O_{2peak}$ group, (ii) do the significant differences between the LOW and HIGH groups ranked for CP remain, and (iii) does the significant correlation between CP and TTE at CP remain?

In order to answer these questions the same analyses performed in section 8.2.2 have been repeated but the two outlying data points have been omitted. Equivalent group sizes were maintained for $\dot{V}O_{2peak}$ - and CP-ranked groups, which meant replacing the outlying data points with successive data points where necessary. The results are displayed in table 8.4.

Table 8.4: Mean ± SEM time to exhaustion (TTE) in min at Critical Power (CP) for groups based on $\dot{V}O_{2peak}$ and CP rankings, omitting outliers

| | | n | TTE (min) | *P value* |
|---|---|---|---|---|
| $\dot{V}O_{2peak}$ rankings (n = 23) | LOW | 8 | 23.2 ± 3.0 | |
| | MOD | 7 | 25.7 ± 3.1 | *0.205* |
| | HIGH | 8 | 18.2 ± 2.7 | |
| CP rankings (n = 23) | LOW | 8 | 23.7 ± 3.1 | |
| | MOD | 7 | 24.1 ± 3.0 | *0.435* |
| | HIGH | 8 | 19.1 ± 3.0 | |
| $\dot{V}O_{2peak}$ rankings ([2 x n=8]) | LOW | 8 | 23.2 ± 3.0 | *0.225* |
| | HIGH | 8 | 18.2 ± 2.7 | |
| CP rankings ([2 x n=8]) | **LOW** | **8** | **23.7 ± 3.1** | *0.299* |
| | HIGH | 8 | 19.1 ± 3.0 | |

No significant differences between groups: P > 0.05 (significant differences evident in table 8.3 but not in table 8.4 are highlighted in **bold**)

Table 8.4 shows that removing the outliers had a considerable impact on the CP-based LOW group (both outliers were originally part of this group) and this is reflected in the higher P values and no significant differences between the LOW and HIGH CP-ranked groups. The relationship between TTE at CP and $\dot{V}O_{2peak}$ remained non-significant after excluding the outlying data points (n = 23, r = -0.21, P = 0.342; figure 8.3*a*). However, despite no significant difference between the two distinct CP-ranked groups, the significant correlation between TTE at CP and CP remained (n = 23, r = -0.45, P = 0.033; figure 8.3*b*). Therefore, the possibility that cycling at a lower CP is tolerable for a longer duration cannot be discounted and this may be due to LOW CP individuals working at a lower relative intensity and, therefore, working within a less severe exercise-intensity domain.

These findings affect the hypotheses regarding physiological responses to cycling at low or high power outputs. For example, at the end of section 8.2.2 it was proposed that absolute power output may affect physiological responses (i.e., $\dot{V}O_2$, $[La^-]_{bl}$ and HR), since those cycling at a lower CP tolerated the exercise for longer. While the new correlation between TTE at CP and CP (omitting outliers) continues to support this theory), there were no differences in the group mean TTE values for the LOW and HIGH fitness groups. Whether absolute power output is related to the

physiological responses to exercise at CP will be investigated in the next sub-section using a case-study approach.
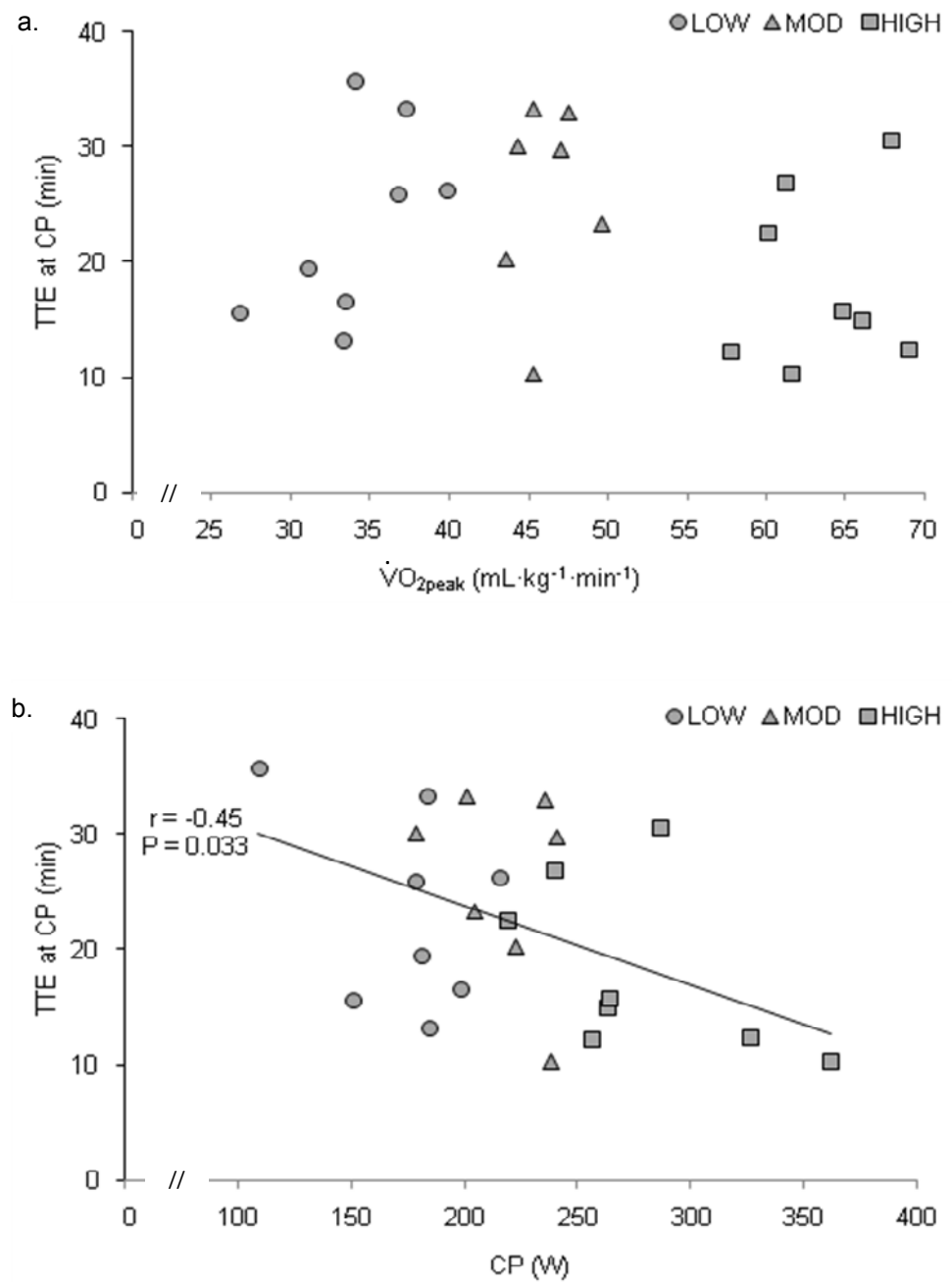


Figure 8.3: Time to exhaustion at Critical Power (TTE at CP) in min related to a.) $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$) and b.) Critical Power (W), omitting outliers

*8.2.4) Time to exhaustion at Critical Power: a case-study approach*

The purpose of this final sub-section is to examine individual physiological responses to exercise at CP. Two specific questions have been developed and will be considered in turn:

1. Are the physiological responses to exercise at CP different at higher power outputs?

2. Are the physiological responses to exercise at CP different when TTE is long or short?

*1. Are the physiological responses to exercise at Critical Power different at higher power outputs?*

In section 7.5.2 no differences were reported between the three fitness groups at any time points for $\dot{V}O_2$, $[La^-]_{bl}$ or HR during exercise at CP. However, figure 7.8 reflects responses normalised to a proportion of total TTE, so rates of change would be concealed. Therefore, in order to determine whether physiological responses to exercise at CP over similar time periods are different at higher power outputs, two low- versus high-CP pairs of individuals have been compared (table 8.5). The data in table 8.5 show that absolute CP values differ within each pair, but that TTE values were matched as closely as possible. The $\dot{V}O_2$, $[La^-]_{bl}$ and HR responses for the two pairs (i.e., four individuals) are displayed in figure 8.4.

Table 8.5: Individual characteristics for two low- versus high-Critical Power (CP) pairs with similar exhaustion times at CP

| Participant | TTE at CP (min) | Pair | CP (W) | CP (% of MMP) | $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$) | $\dot{V}O_2$ -SC (L·min$^{-1}$) |
|---|---|---|---|---|---|---|
| Low CP | 15.5 | Short TTE | 151 | 67 | 26.8 | 0.29 |
| High CP | 15.8 | | 264 | 77 | 64.8 | 0.86 |
| Low CP | 30.0 | Long TTE | 179 | 72 | 44.4 | 0.31 |
| High CP | 29.7 | | 241 | 68 | 47.1 | 0.64 |

TTE = time to exhaustion; $\dot{V}O_2$ -SC = $\dot{V}O_2$ -slow component
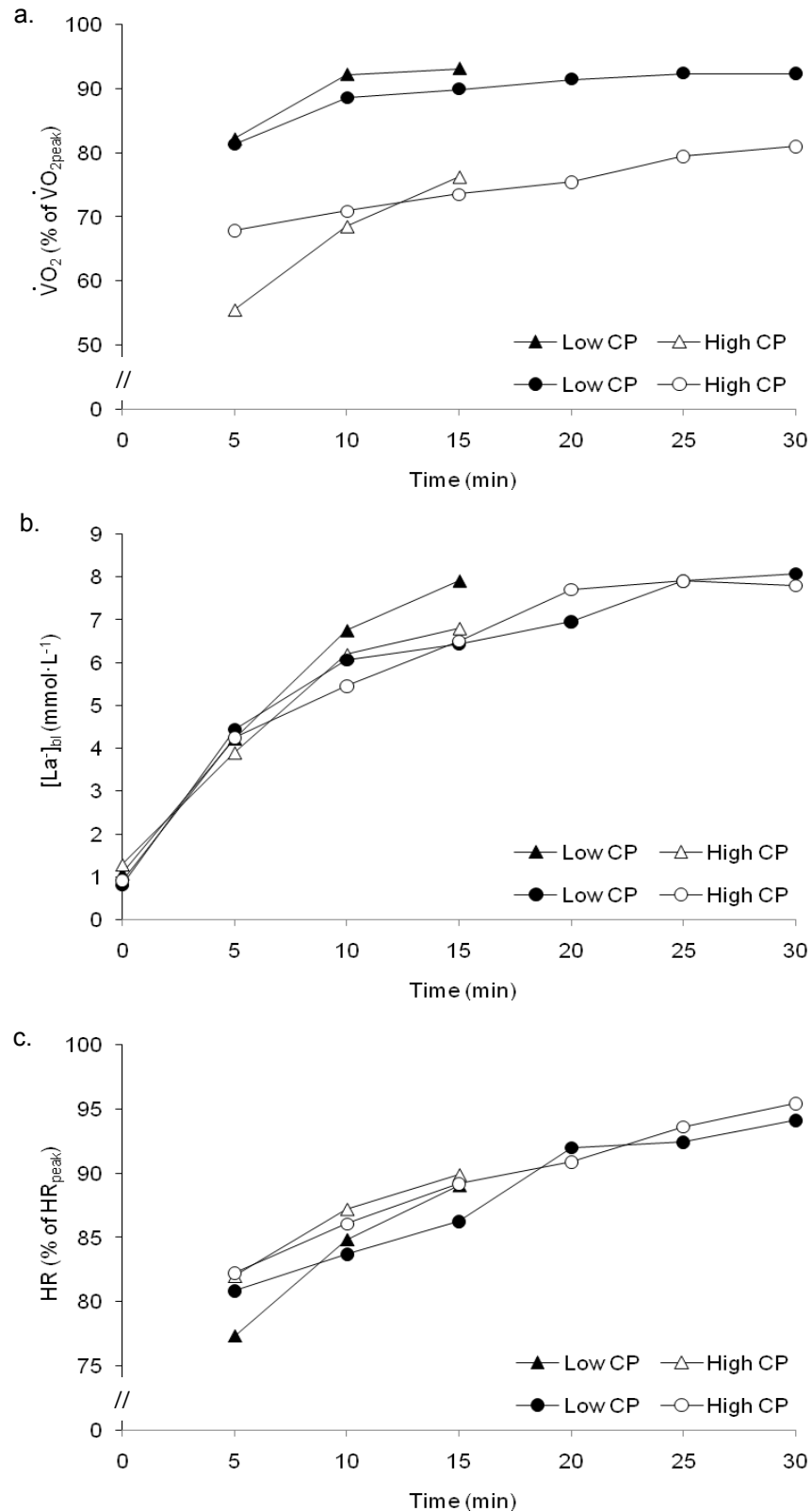
Figure 8.4: a.) V̇O₂ , b.) blood lactate concentration ([La⁻]bl) and c.) heart rate (HR) responses to exercise at Critical Power (CP) for two low- versus high-CP pairs (triangles represent the short TTE pairing; circles represent the long TTE pairing)

Within-pair comparisons in figure 8.4 show that individual $[La^-]_{bl}$ and HR responses were similar for the low- and high-CP individuals. For the short TTE pairing who ceased exercise at CP after $\sim$ 15 min (triangular markers), $[La^-]_{bl}$ increased steadily throughout exercise and reached a peak at $\sim 7 - 8$ mmol·L$^{-1}$. For the long TTE pairing who ceased exercise at CP after $\sim$ 30 min (circular markers), the increase in $[La^-]_{bl}$ became less severe over time but the peak was similar at $\sim$ 8 mmol·L$^{-1}$. Although small inter-individual differences are evident, these appear negligible. Similarly, the differences in HR responses between the low- and high-CP individuals appear minor. These data imply that high-CP individuals experience similar physiological responses as low-CP individuals during exercise at CP, despite working at higher absolute intensities. This appears to be independent of relative CP (i.e., as a % of MMP), which was lower for the low- versus high-CP individual in the short TTE pairing but higher for the low- versus high-CP individual in the long TTE pairing (table 8.5). Although the findings support absolute CP as a valid marker of relative exercise stress, the doubled TTE for the long TTE pairing compared with the short TTE pairing, coupled with the higher end HR in the long- compared with the short-TTE pairing (by $\sim$ 5 % of HR$_{peak}$), demonstrate potential limitations to the use of CP as a training intensity or as a marker of aerobic endurance.

The $\dot{V}O_2$ data present further limitations to the practical application of CP, with $\dot{V}O_2$ responses differing between individuals with low- versus high-CP values, and between individuals with similar CP values but different TTE responses to exercise at CP. The only consistent patterns show that low-CP individuals develop a $\dot{V}O_2$ of $\sim$ 90 % of $\dot{V}O_{2peak}$ and high-CP individuals develop a $\dot{V}O_2$ of $\sim$ 80 % of $\dot{V}O_{2peak}$. This is not explained by a higher $\dot{V}O_2$-SC in the low-CP individuals (calculated by subtracting the 5-min $\dot{V}O_2$ from the end-exercise $\dot{V}O_2$), as these values were considerably higher in the high-CP individuals (table 8.5). Instead, it is possible that the higher $\dot{V}O_2$ responses in the low-CP participants may be due to a training effect over time, as suggested in section 7.6.3.

*2. Are the physiological responses to exercise at Critical Power different when time to exhaustion is long or short?*

While this question was approached to some extent in the previous analysis, the CP values in question 1 were deliberately dissimilar between the pairs. In order to respond to the current question, two pairs of individuals will be physiological matched as closely as possible but TTE at CP will differ. The purpose of these pairings is to investigate the potential explanations for different exhaustion times, a variant of aerobic endurance, despite similar absolute power output values. Characteristics for the two pairs of low- versus high-TTE individuals are displayed in table 8.6 and their physiological responses to exercise at CP are illustrated in figure 8.5.

Table 8.6: Individual characteristics for two low- versus high-Critical Power (CP) pairs with different exhaustion times at CP

| Participant | Pair | TTE at CP (min) | P-LT (W) | CP (W) | MMP (W) | $\dot{V}O_2 - CP_{est}$ (% of $\dot{V}O_{2peak}$) | $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Low TTE | 1 | 13.2 | 125 | 185 | 265 | 79 | 33.4 |
| High TTE | | 33.3 | 100 | 184 | 240 | 84 | 37.4 |
| Low TTE | 2 | 30.0 | 100 | 179 | 250 | 69 | 44.4 |
| High TTE | | 60.0 | 100 | 168 | 250 | 72 | 45.9 |

TTE = time to exhaustion; P-LT = power output associated with lactate threshold; MMP = maximal minute power; $\dot{V}O_2 - CP_{est}$ = estimated $\dot{V}O_2$ associated with CP
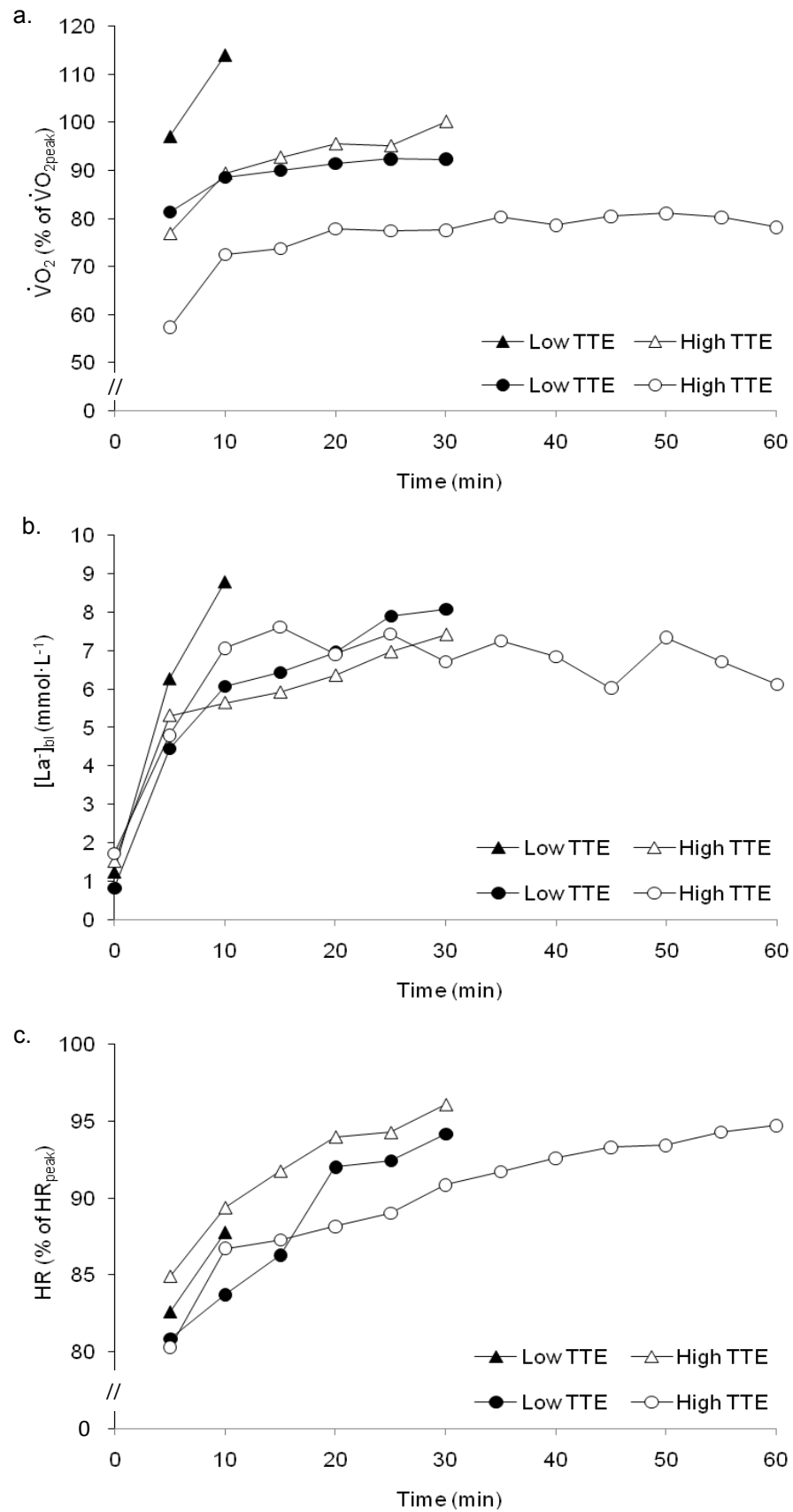
Figure 8.5: a.) V̇O₂ , b.) blood lactate concentration ([La⁻]bl) and c.) heart rate (HR) responses to exercise at Critical Power for two low versus high time to exhaustion (TTE) pairs (triangles represent pair 1; circles represent pair 2)

The inconsistent responses to exercise at CP between individuals are complex. The patterns of change over time for $[La^-]_{bl}$ and HR appear to be similar for both pairs of individuals, despite substantial differences in TTE. The only clear differences, again, are in the $\dot{V}O_2$ data. A visual analysis shows that the individual who was exhausted after 13.2 min (filled triangles) was unable to attain a physiological steady state and, despite an estimated $\dot{V}O_2$ at CP of 79 % of $\dot{V}O_{2peak}$, actual $\dot{V}O_2$ was ~ 97 % of $\dot{V}O_{2peak}$ after 5 min and more than 100 % of $\dot{V}O_{2peak}$ after 10 min (i.e., just prior to exhaustion). By contrast, the high TTE individual in pair 1 (unfilled triangles) was able to attain a relatively steady state in $\dot{V}O_2$, exercising at ~ 80 and 90 % of $\dot{V}O_{2peak}$ after 5 and 10 min, respectively (compared with an estimated $\dot{V}O_2$ at CP of 84 % of $\dot{V}O_{2peak}$). The low TTE individual in pair 2 (filled circles) exercised for a similar time period and had a very similar $\dot{V}O_2$ response, again exercising at ~ 80 and 90 % of $\dot{V}O_{2peak}$ after 5 and 10 min, respectively (compared with an estimated $\dot{V}O_2$ at CP of 69 % of $\dot{V}O_{2peak}$). The high TTE individual in pair 2 (unfilled circles), however, had a $\dot{V}O_2$ of ~ 57 % of $\dot{V}O_{2peak}$ after 5 min and attained a $\dot{V}O_2$ steady-state at ~ 79 % of $\dot{V}O_{2peak}$ (compared with an estimated $\dot{V}O_2$ at CP of 72 % of $\dot{V}O_{2peak}$). These data suggest that $\dot{V}O_2$ after 5 – 10 min may be a useful predictor for TTE during exercise at CP for individuals with CP and $\dot{V}O_{2peak}$ values of 168 – 185 W and 33 – 46 mL·kg$^{-1}$·min$^{-1}$, respectively. Conversely, $\dot{V}O_2$ -CP$_{est}$ does not appear to relate to TTE within this population. The findings show that exercise at CP spans a range of exercise-intensity domains for individuals broadly matched for P-LT, CP, MMP and $\dot{V}O_{2peak}$ (i.e., a range of aerobic fitness markers).

*8.2.5) Summary of time to exhaustion at Critical Power*

The key messages from the current section may be summarised as follows:

- despite the tendency observed in chapter 7, TTE at CP does not decrease as groups increase in $\dot{V}O_{2peak}$;
- a negative correlation exists between TTE at CP and CP, such that a higher absolute CP tends to elicit shorter exhaustion times during exercise at CP;

- individuals with a high CP experience similar $[La^-]_{bl}$ and HR responses as individuals with a low CP during exercise at CP;

- individuals with a high CP experience lower $\dot{V}O_2$ responses to exercise at CP compared with individuals with a low CP;

- patterns of change in $[La^-]_{bl}$ and HR are similar during exercise at CP between individuals matched for aerobic fitness, despite very different exhaustion times;

- the $\dot{V}O_2$ after $5 - 10$ min of exercise at CP may be used to predict TTE in individuals of low-to-moderate aerobic fitness;

- the variability of TTE, $\dot{V}O_2$ and HR responses among individuals during exercise at CP limit the general use of CP for training or monitoring exercise.

## 8.3) Modelling Critical Power

Having focused more closely in the previous two sections on CP as an aerobic fitness parameter and the responses to exercise at CP, respectively, the current section aims to establish the sensitivity of CP modelling and the potential impacts of modelling errors on the CP estimate. Three specific questions relating to CP modelling that have arisen out of the literature will be approached and investigated using the data presented in chapter 7:

1. To what extent do longer-duration exhaustive trials affect CP estimates?
2. What CP-related exercise intensity can be maintained for 60 min?
3. Does estimated TTE at 105 % of CP differ from actual TTE at 105 % of CP?

*8.3.1) To what extent do longer-duration exhaustive trials affect Critical Power estimates?*

In order to minimise the effects of aerobic inertia that are inherent to very short-duration TTE trials, and to avert the confounding effects of dehydration, boredom and muscle glycogen depletion during longer trials, Hill (2004) suggested that CP modelling should restrict exhaustive trial durations to $\sim 3 - 15$ min. Considering this recommendation, and given the original physiological basis of the CP model, it was outlined in section 7.2.5 that TTE trials lasting < 3 or > 15 min would be excluded

from the CP modelling process. However, the additional TTE data obtained during the trials at 95, 100 and 105 % of CP within part 2 of chapter 7 provide an opportunity to explore the effects of including longer-duration data points within the CP model.

The evidence outlined in section 2.2.2 showed that longer-duration exhaustive trials (attained by using lower work rates) result in lower CP estimates (Bishop *et al.*, 1998; Jenkins *et al.*, 1998; Vautier *et al.*, 1995). This concept may be visualised through figure 2.4, where CP is represented by the asymptote of the P-t relationship. That is, the parameter estimate will always be lower than the lowest work rate used within the model. As such, it is expected that the inclusion of P-t$^{-1}$ data points from exhaustive trials at and below CP will produce parameter estimates significantly lower than the original CP estimate.

To understand more fully the effects of using longer-duration data points a series of modifications have been made to the original modelling process used in chapter 7. Full data sets were only available for n = 14 (of the original 25) since (i) all trials terminated at 60 min were excluded, and (ii) participants who did not produce exercise durations that became progressively longer as exercise intensity decreased (from 105 to 100 to 95 % of CP) were excluded. Results are displayed in table 8.7. The first row (i.e., the 'CP' model) represents the CP parameter estimated from the original CP-determination data used in chapter 7. The following three rows (CP+105, CP+100 and CP+95) represent the new parameter estimates obtained by including TTE data from the trial at 105, 100 or 95 % of CP to the original CP determination data. The final row of data, 95+100+105, represents a parameter estimate derived only from the data points obtained during the trials below, at and above CP. A graphical example of the five derivations of parameter estimates for one individual is illustrated in figure 8.6.

Table 8.7: Mean ± SEM parameter estimates from the original Critical Power (CP) modelling data and additional P-t$^{-1}$ data points from the trials at 95, 100 and 105 % of CP (n = 14)

| Model | Trial duration range (min) | Parameter estimate (W) | (% of CP) | (% of MMP) | r |
|---|---|---|---|---|---|
| CP | 3 – 15 | 243 ± 13 | 100 ± 0.0 | 75 ± 1 | 0.99 ± 0.002 |
| CP+105 | 3 – 25 | 238 ± 13* | 98 ± 0.4 | 73 ± 1 | 0.99 ± 0.002 |
| CP+100 | 3 – 33 | 235 ± 13* | 97 ± 0.5 | 72 ± 1 | 0.98 ± 0.003 |
| CP+95 | 3 – 51 | 231 ± 13* | 95 ± 0.4 | 71 ± 1 | 0.98 ± 0.007 |
| 95+100+105 | 4 – 51 | 211 ± 14* | 87 ± 2.1 | 65 ± 2 | 0.96 ± 0.009 |

Significantly different from the CP estimate: * P < 0.001
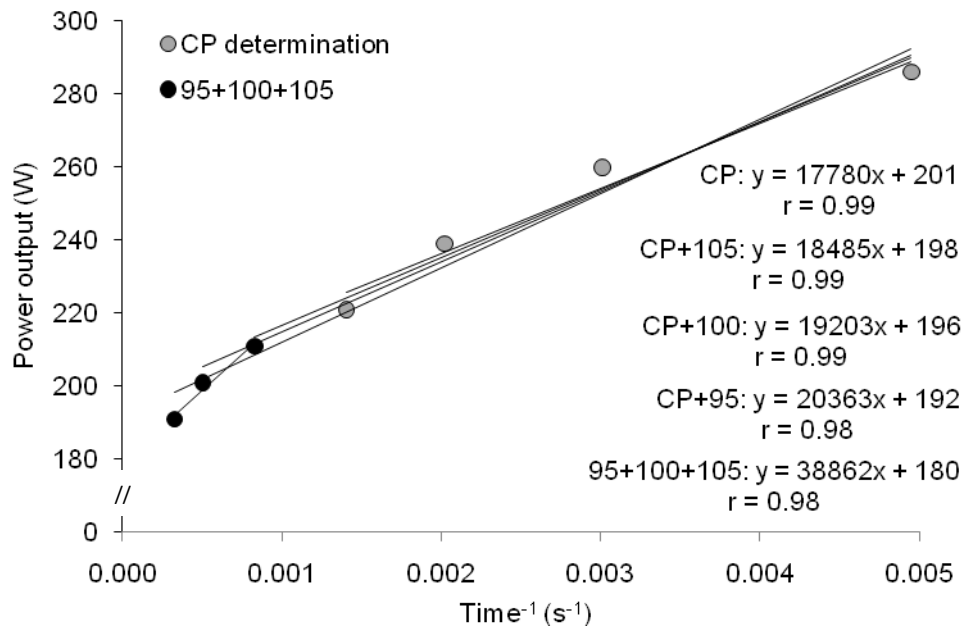


Figure 8.6: The five parameter estimates for one individual using (i) the four original Critical Power data points (CP; grey-filled circles), (ii) the four original data points plus the 105, 100 or 95 % data point (CP+105, CP+100 and CP+95) and (iii) the 95, 100 and 105 % data points only (95+100+105; black-filled circles)

The group data displayed in table 8.7 show that large increases in trial duration (i.e., upper range values increasing from 15 min to 51, 33 and 25 min when including trials at 95, 100 and 105 % of CP, respectively) have a relatively small effect on reducing CP (i.e., reductions of less than 18 W, or 7 %, in all cases). McLellan and Cheung (1992) reported a similarly small change in CP when adding TTE at CP (lasting ~ 20 min) to the original CP determination data points, with a reduction in the mean parameter estimate of only 7 W. However, although these changes in CP appear small, the differences from the original CP estimate were significant (P < 0.001) with

the biggest effect occurring when the data point from the trial at 95 % of CP was included. This new CP parameter estimate was equivalent to 95.0 ± 0.4 % of the original estimate, which, as shown in part 2 of chapter 7, leads to significantly altered physiological responses during exercise when compared with exercise at 100 % of CP. Therefore, while CP appears reasonably robust against large changes in the upper limit of t in the P-t$^{-1}$ relationship (which is further reflected in the data from the 95+100+105 model, whereby the TTE range increases substantially but the impact on the CP parameter estimate is comparatively small), the physiological effects of small changes in CP when exercising at CP are actually substantial. These findings highlight the importance of accurately imposing work rate if a practical aim is to routinely use CP as an intensity to exercise at, since TTE and $\dot{V}O_2$ responses during exercise at and around CP are highly sensitive.

A further consideration when determining and subsequently using CP is the level of confidence in the parameter estimate. For example, when three or more data points are used within the linear P-t$^{-1}$ model, the 95 % confidence interval (CI) can be calculated by multiplying the SEE by the t value for the degrees of freedom (*df*) within the model (i.e., number of data points − 1):

$$95 \text{ % CI} = \text{SEE x t}(df) \qquad\qquad \textit{equation 10}$$

For the example in figure 8.6, the 95 % CI for the original CP parameter estimate of 201 W (grey-filled circles) is given by the SEE (4.1 W) multiplied by the t value for *df* = 3 (2.353), which gives a confidence value of 9.7 W. This 95 % CI reflects ~ 5 % of the original CP parameter estimate (i.e., 9.7 / 201 W = 4.8 %), which may explain the inter-individual differences during exercise at CP highlighted throughout this and the previous chapter. That is, the CP estimate for one individual may, in fact, reflect 95 % of their 'true' CP, while the CP estimate for another individual may reflect 105 % of their 'true' CP. These errors in the CP parameter estimate would presumably result in different TTE and physiological responses during exercise at CP, as highlighted in chapter 7 for exercise at 95 % and 105 % of CP.

*8.3.2) What Critical Power-related exercise intensity can be maintained for 60 min?*

Early on in this thesis the CP construct was introduced as reflecting an exercise intensity that is theoretically sustainable for an infinite amount of time, based on the original definition (Scherrer & Monod, 1960). Therefore, due to the nature of the CP model, predicting a power output that will lead to fatigue within 60 min will always generate a parameter estimate of P > CP. For example, the CP-determination models from chapter 7 for n = 25 reveal that the mean ± SD power output sustainable for 60 min would be 224 ± 55 W, or 102 ± 0.9 % of CP. While this model predicts that exercise very close to 100 % of CP can be maintained for 60 min, data from previous studies (see table 7.1) and this thesis challenge the notion that exercise at CP would be sustainable for 60 min. The aim of the present analysis was to use the data from chapter 7 to determine a more accurate CP-related exercise intensity that would be sustainable for 60 min.

In order to answer the current research question the trials completed at 95, 100 and 105 % of CP were used to re-model the P-t$^{-1}$ relationship and predict the power output that is sustainable for 60 min. A similar method has been used previously by Housh *et al.* (1989), who measured TTE during exhaustive exercise at 79, 97, 120, 140 and 160 % of CP. Using these five new data points the authors derived a second P-t relationship to estimate the intensity that would correspond to a TTE of 60 min. The process of generating a second P-t$^{-1}$ relationship using the three exhaustive trials at 95, 100 and 105 % of CP in the current study was completed in section 8.3.1 and an example for one individual is illustrated in figure 8.6 (black filled circles). For this participant the new 95+100+105 relationship was given by y = 38862x + 180 (where y represents P and x represents t$^{-1}$). At t = 60 min this equation generates an estimated P of 190 W, which is equivalent to 94.7 % of the individual's original CP. Mean ± SD group data for n = 14 (i.e., the sub-group defined in section 8.3.1) reveals that the sustainable power output for 60 min is estimated at 222 ± 48 W, or 92 ± 4 % of the original CP (individual values ranged from 80 – 95 %).

These calculations highlight the impact of trial duration on the predictive value of the CP model. For example, when using trials lasting 3 – 15 min the predicted intensity

sustainable for 60 min was 102 % of the original CP. However, when adding trials lasting up to 51 min the predicted intensity was a more realistic 92 % of the original CP. The mean value of 92 % of CP is greater than the 83 % value that was estimated by Housh *et al.* (1989). This discrepancy is likely to be due to the lowest-intensity trial within the re-modelling process applied by Housh *et al.* (1989) to be equivalent to 79 % of CP, which lasted 58 min on average, compared with 95 % used in the present re-modelling process, which lasted only 32 min on average. This comparison between data from the present study and that presented by Housh *et al.* (1989) demonstrates that the estimated proportion of originally-modelled CP sustainable for 60 min is dependent upon the duration of the trials used within the model. However, both studies support the notion that power outputs of ~ 80 – 95 % of CP would be sustainable for 60 min. Therefore, the practical suggestion at the end of section 4.2.1 (i.e., that exercise at 85 – 95 % of CP would probably lead to exhaustion in ~ 60 min) would be more accurate if the lower boundary were reduced to 80 %. The current analyses have shown that the traditional CP model is inaccurate when predicting exercise duration for intensities that lie outside of the range used within the model. This will be considered further in the next section.

*8.3.3) Does estimated time to exhaustion above Critical Power differ from actual time to exhaustion above Critical Power?*

The final question within the current section aims to support the predictive ability of the P-t$^{-1}$ model for P > CP. The standardised trials performed above CP within chapter 7 of the present thesis were those at 105 % of CP and at MMP (which was equivalent to mean ± SD: 137 ± 10 % of CP). They have been selected for comparison as they span the range of durations (and intensities) used for CP modelling. The predicted and actual TTE values for those trials are displayed in table 8.8 for n = 18 (i.e., all participants who completed trials at both 105 % of CP and MMP). Paired t-tests revealed that actual TTE did not differ from predicted TTE at MMP, or 137 % of CP (P = 0.567), but that actual TTE was significantly shorter than predicted TTE at 105 % of CP (P < 0.001). These findings support the CP model in being able to predict TTE for P > 105 % of CP, which is consistent with the data presented by Housh *et al.* (1989), who showed differences between predicted and

actual TTE during exhaustive exercise at 120, 140 and 160 % of CP to be non-significant (table 4.1, section 4.2.1). The difference between predicted and actual TTE at 105 % of CP confirms the limitation of the P-t$^{-1}$ model in predicting TTE when the exercise intensity lies outside the range of CP-determination trials. For example, exercise at MMP is included within the range of intensities over which the CP model functions. With greater reliance on anaerobic energy provision, the metabolic factors contributing to exhaustion at MMP would presumably be more predictable by the model. Alternatively, the reduced predictive capability of the P-t$^{-1}$ model for P close to CP (i.e., 105 % of CP versus MMP) could be participant motivation, which has been suggested to have a greater impact on TTE over longer trials (Hopkins *et al.*, 2001).

Table 8.8: Mean ± SEM for predicted and actual time to exhaustion (TTE) for exercise at maximal minute power (MMP) and 105 % of Critical Power (CP)

| Trial | Power Output (W) | Predicted TTE (s) | Actual TTE (s) | r |
|---|---|---|---|---|
| MMP | 311 ± 13 | 207 ± 9 | 209 ± 9 | 0.95* |
| 105 % of CP | 242 ± 12 | 1552 ± 112 | 910 ± 66** | 0.66* |

Significantly different from predicted value: ** $P < 0.001$; significant correlation: * $P < 0.005$

*8.3.4) Summary of practical applications*

In summary, the analyses presented within the current section have shown that:

- the addition of exhaustive trials lasting up to ~ 50 min within the P-t$^{-1}$ model decreases the parameter estimate by only ~ 5 %, although this may have significant consequences during exercise at CP;

- although predictions are dependent upon the duration of the trials used within the model, exercise at 80 – 95 % of CP is estimated to lead to exhaustion in ~ 60 min;

- accurately predicting TTE from P-t$^{-1}$ modelling using trials that last ~ 3 – 15 min is possible for P ≈ 137 % of CP but not P ≤ 105 % of CP.

# 9) Training at Critical Power

## 9.1) Introduction

In section 4.3 a clear gap in the literature was identified whereby, despite the ease of measuring and prescribing exercise at CP, no studies have used CP a stimulus for training. The potential effects of training at CP were highlighted through studies that have prescribed training intensities comparable to CP, i.e., at ~ 60 – 90 % of $\dot{V}O_{2max}$. With observed increases in LT, $\dot{V}O_{2max}$, economy, CS and SDH, it may be expected that repeated exposure to bouts of exercise at CP would induce similar physiological adaptations. Therefore, one aim of the current study is to investigate whether training at CP leads to increases in markers of aerobic fitness (i.e., LT, $\dot{V}O_{2peak}$, economy and muscle enzyme content). In addition, aerobic exercise training close to CP has been shown to increase the CP estimate (Gaesser & Wilson, 1988; Jenkins & Quigley, 1992). Therefore, a further aim of the current study is to confirm previous findings that CP is sensitive to training across a range of aerobic exercise intensities.

The principle of training specificity was introduced in section 4.3.1 and figure 4.2 shows how the effect of training on CP and $\dot{V}O_{2max}$ appears to be specific to the type of exercise performed during the intervention. For example, greater increases in CP were observed following continuous training close to CP compared with lower-intensity continuous and higher-intensity interval training. This implies that changes in CP are not positively related to training intensity but instead, training close to CP has the greatest effect on CP. Likewise, training intermittently around the intensity associated with $\dot{V}O_{2max}$ appears to have a greater effect on $\dot{V}O_{2max}$ compared with lower-intensity continuous training. Similar training specificity principles have been observed for LT, whereby lower-intensity continuous training at LT has led to significant increases in relative LT but not $\dot{V}O_{2max}$ (Henritze *et al.*, 1985).

Specific training adaptations may be attributed to the accumulated acute physiological responses to the different exercise stimuli. For example, in chapters 7 and 8 exercise at CP was identified as stressing central and peripheral mechanisms of $O_2$ delivery and usage and as such, continuous training close to CP would presumably lead to

improvements in both of these systems, i.e., increases in SV and $\dot{Q}_{max}$, more efficient fuel utilisation, reduced $La^-_{bl}$ production and/or improved $La^-_{bl}$ removal and improved muscle buffering capacity (Bassett & Howley, 2000; Bosquet *et al.*, 2002; Gaesser & Poole, 1986; Gibala *et al.*, 2006; Saltin & Strange, 1992). These adaptations would presumably enhance exercise performance during CP-determination trials and, therefore, increase the CP parameter estimate. The precise mechanisms associated with greater increases in $\dot{V}O_{2max}$ following high-intensity interval versus continuous training are difficult to identify, as there are limited mechanistic studies in the literature and participant characteristics and exercise modes often vary. One explanation may be related to more pronounced increases in both maximal arterio-venous oxygen difference (a-$\overline{v}O_2diff_{max}$) and $\dot{Q}_{max}$ during high-intensity work (Daussin *et al.*, 2007). By contrast, adaptations in LT following continuous training are thought to be due to peripheral improvements in the a-$\overline{v}O_2diff_{max}$ without the associated central improvements in $\dot{Q}_{max}$ (Daussin *et al.*, 2007). With reference to the notion of training specificity, the current study aims to identify whether CP is more responsive to training at CP compared with other forms of aerobic training. In addition, training at CP-related intensities close to LT and $\dot{V}O_{2peak}$ will be examined for LT- and $\dot{V}O_{2peak}$-associated responses.

Consistent with increases in aerobic fitness parameters (i.e., LT, CP, $\dot{V}O_{2max}$ and economy), mitochondrial enzyme activities also increase following aerobic-based training (see section 4.3.2 and table 4.2). These responses have been associated with reductions in glycogen catabolism and an improved potential for lipid utilisation (Chesley *et al.*, 1996; Green *et al.*, 1992; Putman *et al.*, 1998; Spina *et al.*, 1996). Specifically, CS, SDH and mitochondrial respiratory chain (i.e., complex I − V) enzymes have been shown to respond positively to aerobic training (Chesley *et al.*, 1996; Daussin *et al.*, 2008; Dubouchaud *et al.*, 2000; Gibala *et al.*, 2006; Gollnick *et al.*, 1973; Spina *et al.*, 1996; Trappe *et al.*, 2006), thereby increasing the maximum rate of oxidative energy provision. These muscle cell adaptations appear to be affected by exercise intensity as well as the duration of the training intervention. For example, while Dubouchaud *et al.* (2000) and Gollnick *et al.* (1973) demonstrated increases of 75 − 95 % in CS and SDH activity after 7 − 9 weeks of training at 75 − 90 % of $\dot{V}O_{2max}$ (see table 4.2), interventions lasting only 5 − 12 days and prescribing

exercise at $\leq 70\%$ of $\dot{V}O_{2max}$ have resulted in CS activity increases of only $20 - 35\%$ (Chesley *et al.*, 1996; Spina *et al.*, 1996) or no significant changes in CS or SDH activity (Green *et al.*, 1992; Green *et al.*, 1991; Phillips *et al.*, 1996; Putman *et al.*, 1998). As such, table 4.2 demonstrates that training at $> 70\%$ of $\dot{V}O_{2max}$ over a period of more than one or two weeks, compared with training at lower intensities for shorter time periods, induces larger changes in muscle mitochondrial enzyme activity and presumably, therefore, oxidative ATP production. A final aim of the current study will be to identify the muscle enzyme responses to training at CP compared with lower-intensity continuous training and higher-intensity interval training.

With time-efficient fitness adaptations a focus of recent physiological research (Burgomaster *et al.*, 2008; Gibala *et al.*, 2006), and with lack of time an influential factor associated with reduced physical activity among adults (Trost *et al.*, 2002), training at CP has relevant practical applications. Compared with training at LT, training at CP would give "more bang for your buck" in terms of fitness gains per time spent exercising. This benefit combines with the practical ease of measuring and applying CP within exercising groups. The evidence shows potentially specific responses to training close to LT, at CP and intermittently around $\dot{V}O_{2max}$. Therefore, the main purpose of the current study is to investigate CP as a training intensity and with total work done (TWD) matched, the following three training interventions will be compared: (i) continuous exercise below CP (i.e., around LT), (ii) continuous exercise at CP, and (iii) intermittent exercise above (i.e., around $\dot{V}O_{2peak}$) and below CP. The two main experimental hypotheses are that:

1. All training groups will experience increases in CP;
2. Training at CP will improve LT, $\dot{V}O_{2peak}$, economy and muscle enzyme content.

In addition, two further hypotheses relating to the specificity of training propose that:

3. Training at CP will lead to greater improvements in CP compared with training below or intermittently around CP;
4. The LT and $\dot{V}O_{2peak}$ parameters will respond more markedly following training below CP and intermittently above CP (i.e., closer to $\dot{V}O_{2peak}$), respectively.

## 9.2) Comparison between two SRM cycle ergometers

### 9.2.1) Rationale for the comparison

The objective of the training study presented in the current chapter was to monitor 48 student participants over an 11-week period. During the two weeks both prior to and following the six-week training intervention, each participant was scheduled to complete an LT test, a RAMP and three or four CP-determination trials. This required 225 – 300 tests being carried out over six days. Due to the intense testing schedule, two SRM cycle ergometers were required (illustration 9.1). Since one of the SRM ergometers was new to the laboratory (the black SRM, right panel), it was considered necessary to assess the reproducibility of data collected during exercise performances using each apparatus. Thus, the purpose of the present methods-related section is to provide comparisons between the measured power output, HR and $\dot{V}O_2$ responses to sub-maximal cycling using the two SRM cycle ergometers. It is hypothesised that no differences would be identified between responses to a repeated exercise protocol.



Illustration 9.1: The two SRM cycle ergometers (left panel: yellow SRM; right panel: black SRM)

### 9.2.2) Procedures

Four experienced cyclists (mean ± SD: age, 33.4 ± 6.0 y; body mass, 68.3 ± 8.8 kg) who were accustomed to laboratory testing and cycle ergometry participated in the present study. Each participant (three females and one male) visited the laboratory on

two occasions and completed 15 min of continuous cycling on each visit. A different SRM cycle ergometer (see section 5.6 for details) was selected for use on each visit such that two participants completed their first test on the yellow SRM ergometer (Y-SRM) and two participants completed their first test on the black SRM ergometer (B-SRM).

The 15-min continuous cycle exercise was broken into three periods of 5 min at increasing workloads ($W_1$, $W_2$ and $W_3$). Workloads were selected with reference to known physiological parameters for each participant (i.e., LT and CP) in order to reflect a range of intensities spanning the moderate and heavy domains. The SRM system recorded second-by-second power output values and average power output was expressed for each of the 5-min periods. The HR data were recorded every 5 s (see section 5.9) and $\dot{V}O_2$ was measured breath-by-breath (see section 5.8.3); these variables were expressed for the final minute of each exercise period. The CV was calculated to reflect within-participant reproducibility for the three variables using *equation 8* and unbiased estimates of the overall mean CV were obtained using *equation 9*. Paired t-tests were used to compare measured power output, HR and $\dot{V}O_2$ responses to exercise for the two cycle ergometers.

*9.2.3) Results*

Individual participant comparisons between the two SRM ergometers for power output, HR and $\dot{V}O_2$ over $W_1$, $W_2$ and $W_3$ are displayed in table 9.1. Individual and adjusted group mean CV data are displayed in table 9.2. Figure 9.1 illustrates the group data for a.) power output, b.) HR and c.) $\dot{V}O_2$. No significant differences were identified between the two SRM ergometers at any of the three exercise intensities ($P > 0.05$).

Table 9.1: Power output, heart rate and $\dot{V}O_2$ data for the two SRM ergometers

| Participant | | Power output (W) | | Heart rate (beats·min$^{-1}$) | | $\dot{V}O_2$ (L·min$^{-1}$) | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| | | Y-SRM | B-SRM | Y-SRM | B-SRM | Y-SRM | B-SRM |
| P1 | $W_1$ | 113 | 125 | 123 | 127 | 1.85 | 1.98 |
| | $W_2$ | 158 | 156 | 138 | 141 | 2.27 | 2.43 |
| | $W_3$ | 208 | 208 | 152 | 152 | 2.84 | 2.89 |
| P2 | $W_1$ | 83 | 81 | 126 | 119 | 1.60 | 1.45 |
| | $W_2$ | 119 | 118 | 151 | 150 | 2.12 | 1.53 |
| | $W_3$ | 159 | 159 | 169 | 169 | 2.99 | 2.13 |
| P3$_m$ | $W_1$ | 123 | 123 | 99 | 107 | 1.69 | 1.70 |
| | $W_2$ | 168 | 168 | 116 | 124 | 2.30 | 2.28 |
| | $W_3$ | 219 | 219 | 132 | 137 | 2.73 | 2.66 |
| P4 | $W_1$ | 104 | 103 | 96 | 102 | 1.37 | 1.59 |
| | $W_2$ | 143 | 143 | 111 | 117 | 1.75 | 1.93 |
| | $W_3$ | 189 | 189 | 128 | 130 | 2.31 | 2.46 |

m = male; Y-SRM: yellow SRM; B-SRM: black SRM

Table 9.2: Individual and adjusted group mean coefficient of variation data for power output, heart rate and $\dot{V}O_2$ for the two SRM ergometers

| Participant | | Power output (%) | Heart rate (%) | $\dot{V}O_2$ (%) |
| --- | --- | --- | --- | --- |
| P1 | $W_1$ | 7.1 | 2.3 | 4.8 |
| | $W_2$ | 0.9 | 1.5 | 4.8 |
| | $W_3$ | 0.0 | 0.0 | 1.2 |
| P2 | $W_1$ | 1.7 | 4.0 | 7.0 |
| | $W_2$ | 0.6 | 0.5 | 22.9 |
| | $W_3$ | 0.0 | 0.0 | 23.8 |
| P3$_m$ | $W_1$ | 0.0 | 5.5 | 0.4 |
| | $W_2$ | 0.0 | 4.7 | 0.6 |
| | $W_3$ | 0.0 | 2.6 | 1.8 |
| P4 | $W_1$ | 0.7 | 4.3 | 10.5 |
| | $W_2$ | 0.0 | 3.7 | 6.9 |
| | $W_3$ | 0.0 | 1.1 | 4.4 |
| GROUP | $W_1$ | 3.7 | 4.2 | 6.7 |
| | $W_2$ | 0.5 | 3.1 | 12.2 |
| | $W_3$ | 0.0 | 1.4 | 12.2 |

m = male
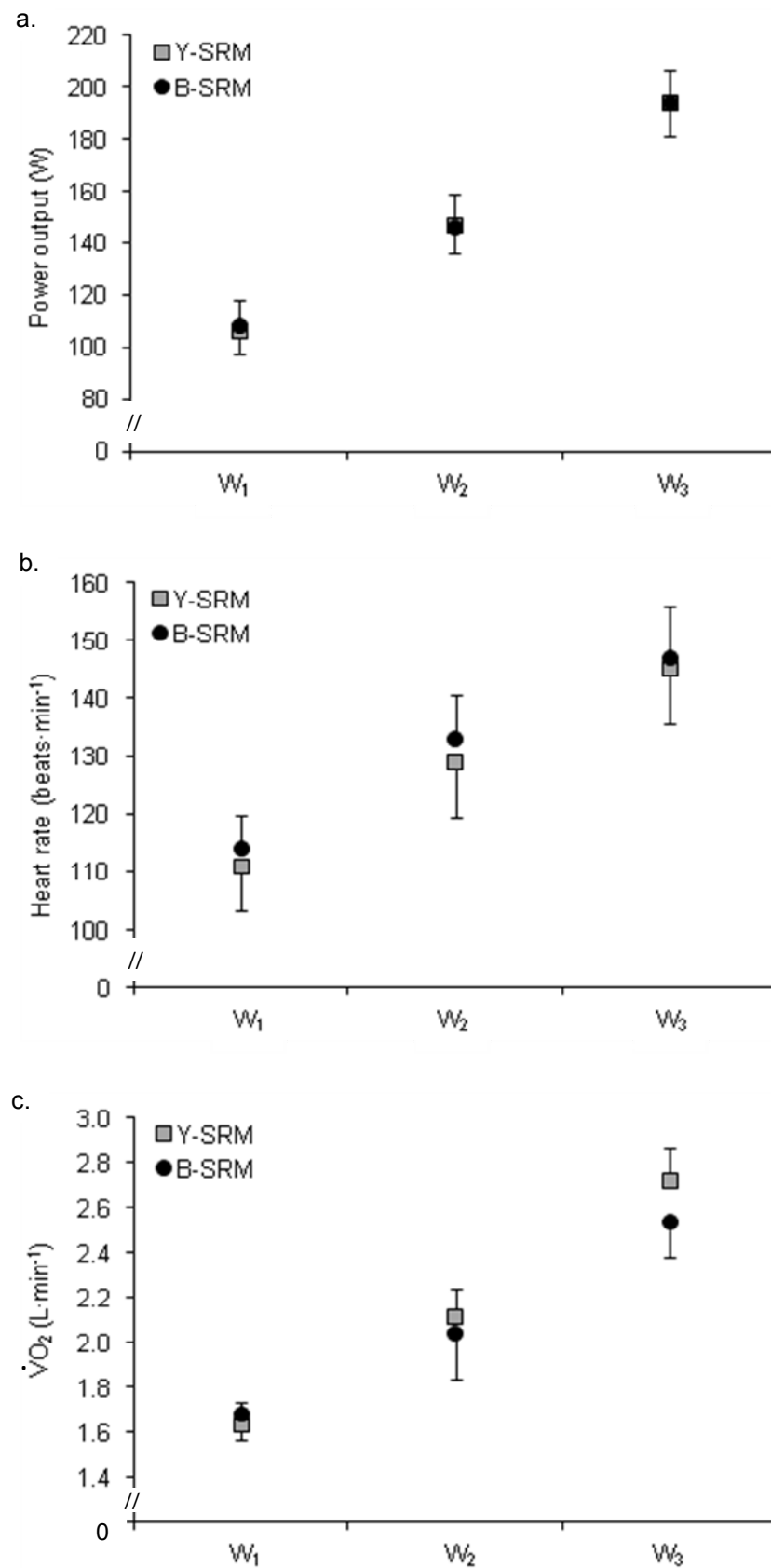
Figure 9.1: Mean ± SEM a.) power output, b.) heart rate and c.) $\dot{V}O_2$ for the two SRM ergometers at the three different work rates

*9.2.4) Implications of the data*

The purpose of the current experiment was to evaluate the measured power output and physiological (HR and $\dot{V}O_2$) responses to sub-maximal exercise using two SRM cycle ergometers. Using a range of intensities over 5-min time periods, paired t-tests revealed no significant differences in any of the three variables between the two ergometers, suggesting that they may be used interchangeably for data collection during the LT, RAMP and CP-determination trials within the training study.

A closer look at the data shows a tendency for greater $\dot{V}O_2$ values to be elicited at higher exercise intensities for the Y-SRM compared with the B-SRM (figure 9.1*c*), particularly during $W_3$. However, this appears to be due to data collected for one participant (P2), who generated considerably larger $\dot{V}O_2$ scores during $W_2$ and $W_3$ in the Y-SRM trial (table 9.1). This observation is supported by the unusually large CV scores for P2 during $W_2$ and $W_3$ (i.e., 22.9 and 23.8 %, respectively), compared with her CV score for $W_1$ (7.0 %) and all the other participants' CV scores for $\dot{V}O_2$ (which ranged from 0.4 – 10.5 %). Previous research has reported day-to-day variations in $\dot{V}O_2$ during sub-maximal exercise of 11 % (Katch *et al.*, 1982), so while CV values of up to 10.5 % may be expected, values beyond 22 % would not.

Further inspection of the 1-min average $\dot{V}O_2$ outputs for P2 during the two trials indicates an elevated $\dot{V}O_2$ response throughout the latter two stages of the Y-SRM trial compared with the B-SRM trial (figure 9.2*b*). This is despite the other three participants exhibiting similar $\dot{V}O_2$ response patterns during the two trials (figures 9.2*a*, 9.2*c* and 9.2*d*). The individual plots presented in figure 9.2 are useful when interpreting data for this small sample group (n = 4) and imply that measurement error may have led to the apparent differences in $\dot{V}O_2$ data for P2.
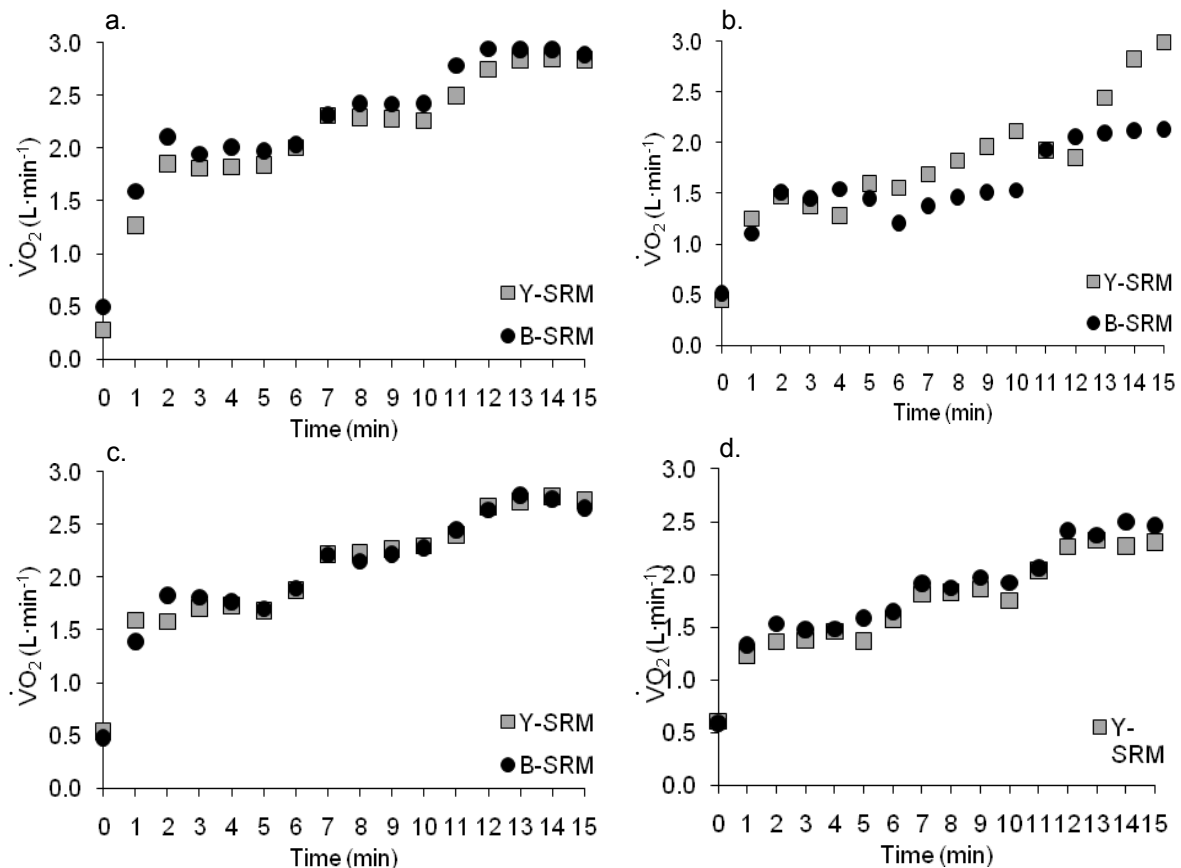
Figure 9.2: Individual $\dot{V}O_2$ responses to sub-maximal exercise for a.) P1, b.) P2, c.) P3 and d.) P4

The CV values for power output and HR (ranging from 0.0 – 7.1 %) were lower than those measured for $\dot{V}O_2$. It appears that the responses were more variable between ergometers at lower exercise intensities, since CV values were higher for $W_1$ compared with $W_2$, and lower for $W_3$ compared with $W_2$. Since power output was averaged over the full 5-min period, the higher CV values during $W_1$ may have been due to the initial acceleration phase at the start of exercise, which would perhaps be more difficult to reproduce than cycling continuously through $W_2$ and $W_3$. However, it is unclear from the data whether CV decreased as a result of power output, exercise duration and/or an acceleration phase. More relevant to the present investigation, perhaps, is that the adjusted mean CV values remained low at < 5 %.

In conclusion, no significant differences were observed in measured power output, HR or $\dot{V}O_2$ responses during sub-maximal exercise using two similar SRM cycle ergometers. The individual responses and CV data suggest that greater variation between cycle ergometers occurs at the onset of exercise, but it is unclear whether this

is due to work rate or absolute time. It would be advisable to commence data collection when using the two SRM ergometers after an initial acceleration phase, in order to overcome the potential variation between cycle ergometers at the onset of exercise. Efforts should also be made to use the same cycle ergometer (i.e., either the Y-SRM or the B-SRM) for a given test both pre- and post-training with each individual when logistically possible. In addition, care needs to be taken when collecting $\dot{V}O_2$ data (i.e., during the calibration, set-up and monitoring of the Ergocard® system) in order to minimise measurement error.

## 9.3) Methods

### 9.3.1) Participants

Thirty-five males and 13 females volunteered to take part in the present study. Participants were assigned to one of three training groups: continuous cycling below CP (<CP), continuous cycling at CP (CP) or intermittent cycling above and below CP ($CP_{INT}$). The three groups each contained 16 participants (with four, four and five females in <CP, CP and $CP_{INT}$ groups, respectively) and were matched for pre-training CP (mean ± SD: 182 ± 40, 183 ± 46 and 183 ± 46 W for <CP, CP and $CP_{INT}$, respectively; P > 0.05). Participants were not well-trained and habitual physical activity questionnaire 'sport index' (HPAQ-SI) scores (Baecke *et al.*, 1982) were similar between groups (mean ± SD: 3.54 ± 0.76, 3.33 ± 0.46 and 3.46 ± 0.67 out of a possible score of 5.00 for <CP, CP and $CP_{INT}$, respectively; P > 0.05). Twenty-seven participants (22 males and five females) volunteered for muscle biopsies and were distributed equally into the three training groups. Five participants (all male) withdrew from the study due to injuries not related to the training intervention and one (from the CP group) was a biopsy volunteer. Pre-training descriptive characteristics for the 43 participants who completed the study are displayed in table 9.3.

Table 9.3: Mean ± SD descriptive data for the three training groups (<CP, CP and $CP_{INT}$)

| Group | M | Age (y) | Body Mass (kg) | F | Age (y) | Body Mass (kg) | All | Age (y) | Body Mass (kg) |
|---|---|---|---|---|---|---|---|---|---|
| <CP | 10 | 21 ± 1 | 78.2 ± 7.9 | 4 | 22 ± 3 | 61.9 ± 7.2 | 14 | 22 ± 2 | 73.5 ± 10.7 |
| CP | 11 | 22 ± 2 | 78.6 ± 9.1 | 4 | 23 ± 3 | 63.8 ± 4.8 | 15 | 22 ± 3 | 74.6 ± 10.5 |
| $CP_{INT}$ | 9 | 21 ± 3 | 72.0 ± 7.0 | 5 | 21 ± 1 | 66.7 ± 12.7 | 14 | 21 ± 2 | 70.2 ± 9.3 |
| All | 30 | 22 ± 2 | 76.5 ± 8.2 | 13 | 22 ± 2 | 64.3 ± 8.4 | 43 | 22 ± 2 | 72.8 ± 10.1 |

M = male; F = female

*9.3.2) Experimental overview*

Table 9.4 provides an overview of the 11-week study. Each participant initially completed two TTE familiarisation sessions on separate days in order to identify SSC and the approximate work rates required for CP determination. The following week an LT test was performed, followed immediately by a RAMP then three (or four, if needed) fixed-power CP determination trials were completed on separate days. The muscle biopsies completed the pre-training testing at the end of the third week. The six-week training intervention commenced in week four and was followed by two final weeks of post-training testing, when participants repeated all pre-training tests except the two familiarisation sessions.

Table 9.4: Overview of the 11-week training study

| | Mon | Tue | Wed | Thu | Fri |
|---|---|---|---|---|---|
| Week 1 | | | TTE Familiarisation Trials | | |
| Week 2 | LT test / RAMP | | CP1 | | CP2 |
| Week 3 | CP3 | CP4 | Muscle Biopsies | | |
| Week 4 | Training (3 x per week) | | | | |
| Week 5 | Training (3 x per week) | | | | |
| Week 6 | Training (3 x per week) | | | | |
| Week 7 | Training (3 x per week) | | | | |
| Week 8 | Training (3 x per week) | | | | |
| Week 9 | Training (3 x per week) | | | | |
| Week 10 | LT / RAMP Tests | | | Muscle Biopsies | |
| Week 11 | CP 1 | CP 2 | | CP 3 | CP 4 |

TTE: time to exhaustion; LT: lactate threshold; RAMP: incremental ramp test to exhaustion; CP1-4: the four TTE trials used for Critical Power determination

*9.3.3) Cycle ergometers*

All pre- and post-training tests were performed on an SRM cycle ergometer (see section 5.6.1 for details). A comparison of the two SRM cycle ergometers used in the present study (Y-SRM and B-SRM) was presented in section 9.2. All training sessions were completed using one of eight Monark cycle ergometers (see section 5.6.1). Where possible, individuals used the same SRM and Monark ergometers for each performance test and training session, respectively. All ergometers were fitted with conventional pedals and toe straps and participants wore trainers while exercising. The SSC (mean ± SD: 82 ± 4 revs·min$^{-1}$) determined during the familiarisation sessions was adhered to throughout the study.

*9.3.4) Lactate threshold and incremental ramp tests*

The LT test was carried out according to the procedures outlined in section 5.7, without expired air collection, and the $\dot{V}O_2$-LT was estimated from the linear relationship between $\dot{V}O_2$ and power output. Typical $[La^-]_{bl}$ responses pre- and post-training for one individual are displayed in figure 9.3. Immediately following the LT test on the Y-SRM, participants completed a RAMP (as described in section 5.8) on the B-SRM. Breath-by-breath gas analysis was carried out as described in section 5.8.3. Individual raw data files were cleaned of any outlying breaths and were converted from breath-by-breath to second-by-second data using interpolation software. The highest $\dot{V}O_2$ recorded over one minute was defined as the $\dot{V}O_{2peak}$ and MMP was calculated according to *equation 6*. Economy was obtained from the gradient of the sub-maximal $\dot{V}O_2$-power output relationship to reflect $O_2$ consumption per unit of power output (Moseley & Jeukendrup, 2001) and was expressed in mL·min$^{-1}$·W$^{-1}$.
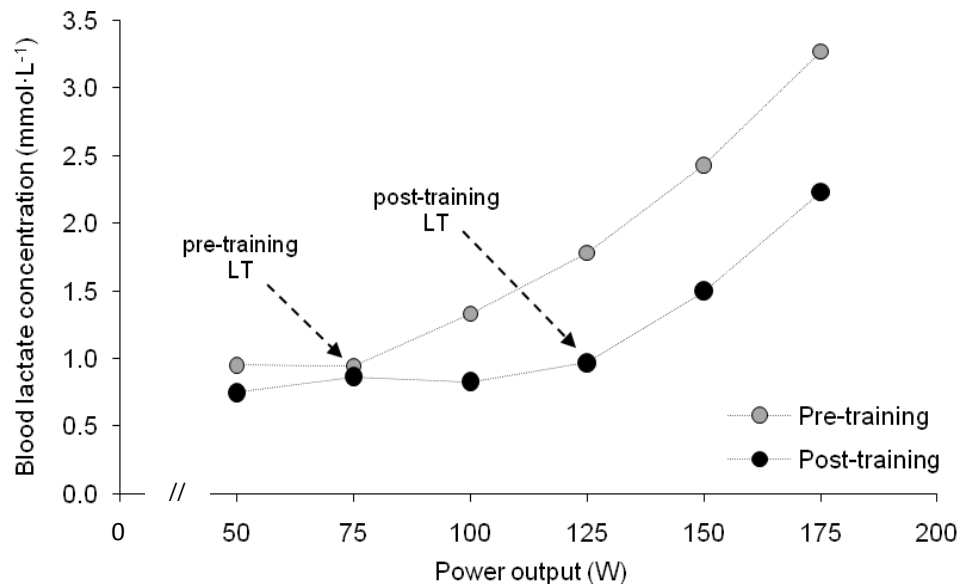
Figure 9.3: Lactate threshold (LT) pre- and post-training for one participant

*9.3.5) Time to exhaustion tests for Critical Power determination*

During the first two laboratory visits participants completed two TTE familiarisation trials at constant workloads that were chosen to lead to exhaustion within ~ 3 – 15 min.  The power output imposed for the first of these trials was selected from table 9.5, which was created using data from the previous main experiment (chapter 7) and provides generic exercise intensities based on participant sex and physical activity levels according to HPAQ-SI scores.  Individuals were verbally encouraged to cycle for as long as possible during the familiarisation sessions and both power output and exercise duration were measured, but were not used for CP determination.

Table 9.5: Power outputs used for the initial time-to-exhaustion familiarisation session based on participant sex and physical activity levels

|  | HPAQ-SI score < 3 | HPAQ-SI score 3 – 3.9 | HPAQ-SI score ≥ 4 |
|---|---|---|---|
| Male | 230 W | 280 W | 330 W |
| Female | 160 W | 220 W | 260 W |

HPAQ-SI: habitual physical activity questionnaire sport index

Following the familiarisation sessions participants completed either three or four constant-load TTE tests (see section 5.10.2) on separate days.  One of the pre-training CP determination trials was completed at 100 % of MMP and one of the post-training

tests was completed at the same absolute intensity (i.e., 100 % of the pre-training MMP). A further post-training test was completed at 100 % of the post-training MMP and all of these trials at MMP were prescribed in a randomised, counter-balanced order. The power output for the initial CP determination test (if not the trial at 100 % of MMP) was estimated from data collected during the familiarisation sessions. Due to the importance of accurately locating CP, and given the sensitivity of CP modelling, an additional condition on the method for determining CP was imposed in the present study. This required one data point to fall within each of the time ranges of 3 – 5, 7 – 10 and 12 – 15 min. Pre- and post-training mean ± SD fits for the $P-t^{-1}$ relationship were r = 0.996 ± 0.004 and r = 0.992 ± 0.010, respectively, while the mean ± SD SEE for CP was 1.79 ± 1.32 W and 2.94 ± 1.83 W pre- and post-training, respectively. Raw data from the pre-and post-training CP determination trials are presented in Appendix H for all participants.

*9.3.6) Training*

The <CP training intensity was equivalent to P-LT. This measure was used to ensure that training below CP, which equated to 77 % of CP (or ~ 53 % of MMP), would approximate the intensity associated with the boundary between moderate- and heavy-intensity exercise. The <CP group exercised at this intensity for 30 min during each training session. The total amount of work that would have been achieved in 30 min at <CP was calculated for all individuals. The CP group then trained at an individually determined amount of time at CP to attain the equivalent amount of work, which resulted in a training duration of 23.2 ± 0.7 min. The $CP_{INT}$ group also trained at an individually determined amount of time to attain the equivalent amount of work, but trained intermittently for 1 min 30 s at 65 % of CP and 30 s at 150 % of CP. These intensities were based on those used by Brickley *et al.* (2006) and they equated to 91 ± 5 and 209 ± 11 % of P-LT, or 45 ± 1 and 103 ± 3 % of MMP. The training duration for $CP_{INT}$ was 25.8 ± 1.3 min.

All groups trained three times per week for six weeks, with all individuals completing a total of 18 training sessions. In order to maintain training responses throughout the intervention period an overload strategy was employed, whereby the TWD was

increased by 5 % after sessions 6, 10 and 14 for all groups through increases in power output. Heart rate data was collected throughout each training session and end-exercise average HR values (HR$_{end}$) were recorded from the penultimate minute (or 2-minute intermittent block for the CP$_{INT}$ group) of each session. The $\dot{V}O_2$ was measured in the third and sixth training weeks and the $\dot{V}O_2$ -SC was calculated as the change in $\dot{V}O_2$ (mL·min$^{-1}$) from the fifth to the final minute of exercise (for the CP$_{INT}$ group, expired air was collected during the 1-min period of lower intensity exercise that immediately preceded the 30 s of higher-intensity exercise). Since exercise duration and work rate differed between groups the $\dot{V}O_2$ -SC was also calculated as a rate, per minute of exercise per W (mL·min$^{-2}$·W$^{-1}$).

*9.3.7) Muscle analyses*

*Muscle biopsies*

Resting muscle biopsies (~ 50 – 200 mg) were obtained from the lateral portion of the right vastus lateralis before and after training. Diagnostic ultrasound was used to accurately identify the depth of the biopsy for each individual, in order to ensure that the correct muscle was located (Webborn *et al.*, 2009). After cleaning the site and following local anaesthesia with 1 % Lidocaine hydrochloride (Hameln Pharmaceuticals, Gloucestershire, UK), an incision of the skin and fascia was made at ~ 20 cm proximal to the superior border of the patella at a depth of ~ 2 cm below the fascia lata. The muscle sample was initially immersed in isopentane to reduce the size of freezing crystals within the muscle (due to the higher thermal conductivity of isopentane compared with liquid nitrogen) before being transferred to liquid nitrogen and subsequently stored at -80$^o$C. The skin incision was repaired using Mersilk Suture (Ethicon, Edinburgh, UK) and participants were monitored daily over the following week in case of any adverse reactions to the muscle biopsy.

*Western blotting*

Muscle samples (~ 40 mg wet weight) were powdered and homogenised in a lysis buffer (1M Tris-HCl, 3.8% SDS, 4M Urea, 20% Glycerol, 0.1% Triton X-100) at a

dilution of ~ 1 μL·mg wet muscle$^{-1}$ and boiled for 5 min. A small quantity of homogenate (~ 5 μL) was used to determine protein concentration using a bicinchoninic acid (BCA) protein assay kit (Pierce, Illinois, USA). The remaining homogenate was stored at -80$^{o}$C and was subsequently analysed for muscle protein using the antibodies outlined in table 9.6.

Table 9.6: Primary and secondary antibodies used to detect three different target proteins

| Target protein | Primary antibody | Secondary antibody | Dilution |
|---|---|---|---|
| Citrate synthase | CISY11-S | Goat anti-rabbit | 1:5000 |
| Succinate dehydrogenase | MS601 | Goat anti-mouse | 1:5000 |
| ATP synthase | MS601 | Goat anti-mouse | 1:5000 |

Sodium dodecyl sulphate-polyacrylamide gel electrophoresis (SDS-PAGE) was used to separate muscle proteins according to their size, a method identified to have a high resolving power and to allow simultaneous multiple protein analyses (McGuigan & Sharman, 2006). Tissue lysates were thawed and prepared with 2 % β-mercaptoethanol and 10 μL of dye before 30 μL was loaded onto 10 % SDS-PAGE gels. The gels were run at 120 V for ~ 2 h in an electrophoresis buffer (illustration 9.2) then were soaked in a transfer buffer for 30 min. The separated proteins were transferred from the gels onto nitrocellulose membranes in a transfer apparatus (BioRad, Hemel Hempstead, UK) using a current of 0.07 A per gel (i.e., 0.35 A for the five gels) for 1 h. After transfer, the membranes were soaked in Ponceau S solution (Sigma, Dorset, UK) for 2 – 3 min then were rinsed in double-distilled water and washed in a Tris-buffered saline with 0.05 % Tween (TBS-T). Visual inspection of the stained membranes ensured that proteins had transferred successfully and that the lanes had been evenly loaded.
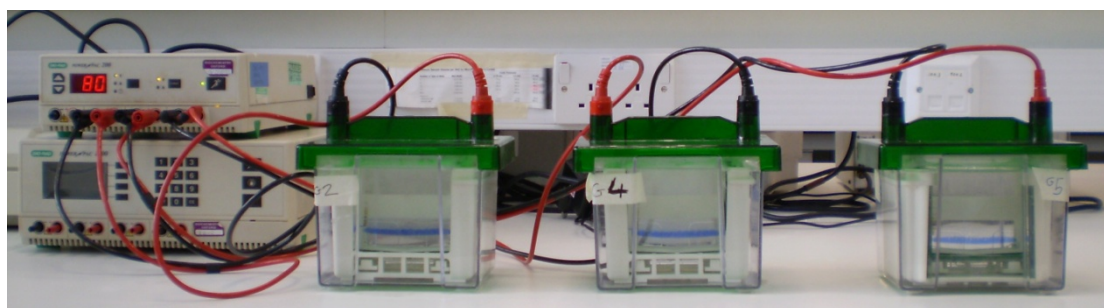


Illustration 9.2: A series of SDS-PAGE gels running in electrophoresis buffer

Following even loading of proteins and successful transfer, membranes were blocked for $1 - 3$ h in TBS-T with 5 % Marvel milk powder (Premier Foods, Hertfordshire, UK) then washed for 1 h in TBS-T, changing the solution every 15 min. Membranes were incubated overnight at 4°C in a 50-ml TBS-T solution containing the primary antibody (table 9.6) and 5 % Marvel. The following morning, membranes were washed for 2 h in TBS-T, incubated at room temperature for 1 h in a 50-ml TBS-T solution containing the secondary antibody (table 9.6) and 5 % Marvel, then washed again for 1 h in TBS-T. Finally, the membranes were treated with Amersham enhanced chemiluminescence (ECL) detection solution (GE Healthcare, Buckinghamshire, UK) and exposed to X-ray film for between 30 s and 10 min. Protein bands were quantified using the commercially available UN-SCAN-IT densitometry software (Silk Scientific, Utah, USA) in order to identify enzyme content.

*9.3.8) Data analyses*

A one-way ANOVA was used to compare training variables (power output, duration, total work done and heart rate) between groups. Homogeneity of variance was checked using the Levene statistic and a post-hoc Tukey test was used to localise the between-group differences. A two-way ANOVA with repeated-measures was used to compare training effects between the three groups. Sphericity was checked using Mauchly's test and the Greenhouse-Geisser correction was used for epsilon < 0.75, while the Huynh-Feldt correction was adopted for less severe asphericity (> 0.75). Within-subject differences were localised using pair-wise comparisons with a Bonferroni adjustment. Pearson's correlations were used to determine relationships between variables.

**9.4) Results**

Data are presented within the current results section according to the chronology of the study. The pre-training data are presented within the first sub-section, the training intervention data in the second sub-section and finally, the effects of training are presented in the third sub-section.

*9.4.1) Pre-training results*

*Lactate threshold and incremental ramp testing*

There were no significant differences between the $<$CP, CP and CP$_{INT}$ training groups for pre-training P-LT expressed in W or as a % of MMP, or $\dot{V}O_2$-LT expressed in mL·kg$^{-1}$·min$^{-1}$ or as a % of $\dot{V}O_{2peak}$ (P $>$ 0.05; table 9.7). Likewise, there were no differences in pre-training MMP, $\dot{V}O_{2peak}$, HR$_{peak}$ or economy values between groups (P $>$ 0.05; table 9.8).

Table 9.7: Mean $\pm$ SEM pre-training data for the power at lactate threshold (P-LT) and the $\dot{V}O_2$ at lactate threshold ($\dot{V}O_2$-LT) for the three training groups

|  | P-LT (W) | P-LT (% of MMP) | $\dot{V}O_2$-LT (mL·kg$^{-1}$·min$^{-1}$) | $\dot{V}O_2$-LT (% of $\dot{V}O_{2peak}$) |
|---|---|---|---|---|
| $<$CP | 89 ± 7 | 33 ± 2 | 21.6 ± 1.4 | 45 ± 2 |
| CP | 97 ± 8 | 35 ± 2 | 22.4 ± 1.8 | 46 ± 3 |
| CP$_{INT}$ | 80 ± 7 | 32 ± 2 | 18.8 ± 1.9 | 41 ± 3 |

No significant differences between training groups: P $>$ 0.05

Table 9.8: Mean $\pm$ SEM pre-training data for maximum minute power (MMP), $\dot{V}O_{2peak}$, heart rate peak (HR$_{peak}$) and economy for the three training groups ($<$CP, CP and CP$_{INT}$)

|  | MMP (W) | $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$) | HR$_{peak}$ (beats·min$^{-1}$) | Economy (mL·min$^{-1}$·W$^{-1}$) |
|---|---|---|---|---|
| $<$CP | 271 ± 15 | 44.8 ± 1.9 | 199 ± 1 | 9.7 ± 0.3 |
| CP | 271 ± 14 | 43.8 ± 1.9 | 193 ± 2 | 9.3 ± 0.4 |
| CP$_{INT}$ | 252 ± 14 | 40.8 ± 2.3 | 193 ± 2 | 9.5 ± 0.5 |

No significant differences between training groups: P $>$ 0.05

*Time to exhaustion trials for Critical Power determination*

The mean $\pm$ SD power outputs prescribed during the two familiarisation sessions were 264 ± 56 and 217 ± 50 W, or 100 ± 8 and 82 ± 7 % of MMP, which led to TTE values of 202 ± 54 and 499 ± 199 s, respectively. These data were used as guidelines for prescribing power outputs for the actual CP determination trials. The durations of the

shortest (TTE$_{short}$), medium (TTE$_{med}$) and longest (TTE$_{long}$) TTE trials for pre-training CP determination are displayed in table 9.9. Average durations fell within the specified ranges of 3 – 5, 7 – 10 and 12 – 15 min and there were no differences in TTE$_{short}$, TTE$_{med}$ or TTE$_{long}$ between the three training groups (P > 0.05). The overall HR values attained at the end of the TTE$_{short}$, TTE$_{med}$ and TTE$_{long}$ trials were (mean ± SEM) 96 ± 1, 96 ± 1 and 95 ± 1 % of HR$_{peak}$ and these values were not different (P = 0.457).

Table 9.9: Mean ± SEM durations (s) for the shortest (TTE$_{short}$), medium (TTE$_{med}$) and longest (TTE$_{long}$) time to exhaustion trials used for pre-training Critical Power determination

|  | TTE$_{short}$ | TTE$_{med}$ | TTE$_{long}$ |
|---|---|---|---|
| <CP | 209 ± 11 | 502 ± 22 | 843 ± 36 |
| CP | 208 ± 14 | 483 ± 31 | 847 ± 19 |
| CP$_{INT}$ | 216 ± 14 | 516 ± 41 | 841 ± 41 |

No significant differences between training groups: P > 0.05

*Critical Power*

There were no significant differences between training groups for pre-training CP or $\dot{V}O_2$ -CP$_{est}$ (P > 0.05) and these data are displayed in table 9.10.

Table 9.10: Mean ± SEM pre-training data for Critical Power (CP) and the estimated $\dot{V}O_2$ at CP ( $\dot{V}O_2$ -CP$_{est}$) for the three training groups (<CP, CP and CP$_{INT}$)

|  | CP (W) | CP (% of MMP) | $\dot{V}O_2$ -CP$_{est}$ (mL·kg$^{-1}$·min$^{-1}$) | $\dot{V}O_2$ -CP$_{est}$ (% of $\dot{V}O_{2peak}$ ) |
|---|---|---|---|---|
| <CP | 187 ± 11 | 69 ± 1 | 34.6 ± 1.4 | 72 ± 1 |
| CP | 184 ± 12 | 68 ± 2 | 33.9 ± 1.8 | 70 ± 1 |
| CP$_{INT}$ | 173 ± 10 | 69 ± 2 | 33.5 ± 1.6 | 74 ± 2 |

No significant differences between training groups: P > 0.05

*Duration, total work done and power output*

Exercise duration did not change over the 18 training sessions. The exercise duration for the <CP group (30.0 ± 0.0 min) was significantly longer than for the CP (22.2 ± 0.7 min) and $CP_{INT}$ (25.8 ± 1.3 min) groups (P < 0.05). Furthermore, the exercise duration was significantly longer for the $CP_{INT}$ compared with the CP group (P = 0.013). Average power output and TWD values for the six-week training period (where a 5 % overload was applied after sessions 6, 10 and 14) are displayed in table 9.11. There were no significant differences in TWD for any of the groups, or in average power output between the <CP and $CP_{INT}$ groups (P > 0.05).

Table 9.11: Mean ± SEM power output (W) and total work done (kJ) for (a) <CP, (b) CP and (c) $CP_{INT}$ groups for each of the four training overload progressions

| a | Overload progression | Power output (W) | Total work done (kJ) |
|---|---|---|---|
| | Sessions 1-6 | 145 ± 10* | 261 ± 17 |
| | Sessions 7-10 | 152 ± 10* | 274 ± 18 |
| | Sessions 11-14 | 160 ± 11* | 288 ± 19 |
| | Sessions 15-18 | 168 ± 11* | 302 ± 20 |
| b | Overload progression | Power output (W) | Total work done (kJ) |
| | Sessions 1-6 | 184 ± 12 | 245 ± 18 |
| | Sessions 7-10 | 194 ± 13 | 257 ± 19 |
| | Sessions 11-14 | 203 ± 13 | 272 ± 20 |
| | Sessions 15-18 | 214 ± 14 | 284 ± 21 |

| | | Power output (W) | | | |
|---|---|---|---|---|---|
| c | Overload progression | *65%CP* | *150%CP* | Average | Total work done (kJ) |
| | Sessions 1-6 | *112 ± 6* | *259 ± 15* | 149 ± 8* | 232 ± 17 |
| | Sessions 7-10 | *118 ± 7* | *272 ± 15* | 156 ± 9* | 243 ± 18 |
| | Sessions 11-14 | *124 ± 7* | *286 ± 16* | 164 ± 9* | 256 ± 19 |
| | Sessions 15-18 | *130 ± 7* | *300 ± 17* | 172 ± 10* | 268 ± 20 |

Significantly different from CP: * P < 0.05

All participants in the <CP and $CP_{INT}$ groups were able to complete the required work during each of the 18 training sessions. However, seven of the CP group were unable

to complete between two and eleven of their training sessions. These individuals received strong verbal encouragement to complete as much of the required time at CP as possible, as the resistance on the cycle ergometer was not reduced. The average training time was $91 \pm 3$ % of the prescribed duration over the 18 sessions for these seven individuals. The actual TWD and duration data have been reported in this section (i.e., in the text and in table 9.11).

*Heart rate*

The mean $\pm$ SEM $HR_{end}$ was significantly lower ($79 \pm 2$ % of $HR_{peak}$) for the <CP group over the 18 training sessions compared with the other two training groups ($89 \pm 1$ and $87 \pm 1$ % of $HR_{peak}$ for CP and $CP_{INT}$ groups, respectively; $P < 0.05$).

*The $\dot{V}O_2$ slow component*

There were no differences in the $\dot{V}O_2$-SC (expressed as a rate of $\dot{V}O_2$, per minute of exercise per W) between training groups during week 3 ($P = 0.059$), but the $\dot{V}O_2$-SC was higher in the CP group compared with the <CP group in week 6 ($P = 0.001$; figure 9.4).
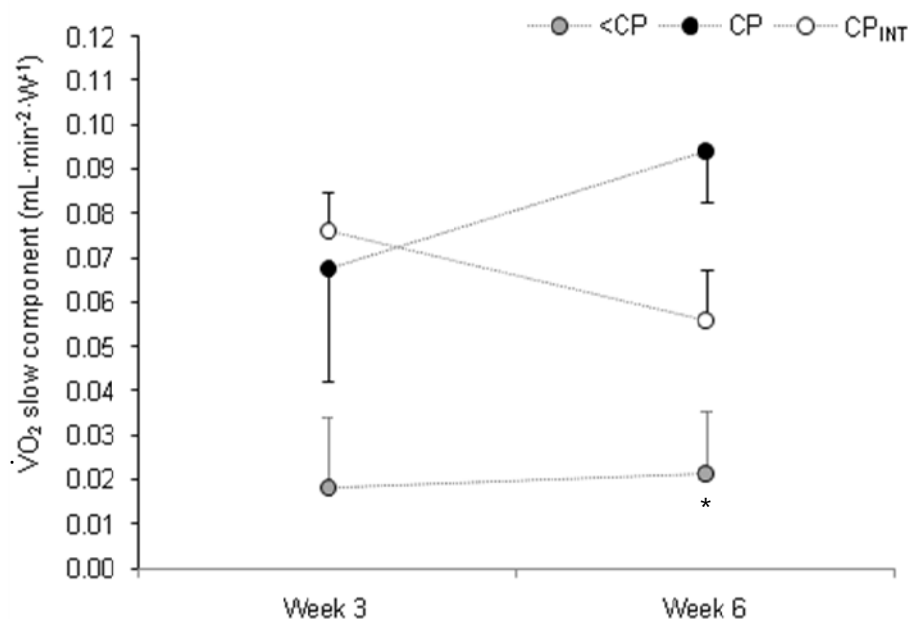


Figure 9.4: The $\dot{V}O_2$ slow component during the third and sixth training weeks
Significantly different from the CP group: * P = 0.001

*9.4.3) Effects of training*

The training data will be presented in the current section with reference to the aims and hypotheses that were outlined in section 9.1. Following the reporting of overall responses, modelling issues and performance data, the first and third hypotheses will be approached. The first hypothesis proposed that CP would be sensitive to training across a range of aerobic exercise intensities and the third hypothesis focused on specificity, predicting that training at CP would lead to the greatest improvements in CP. Following the effects of training on CP, the second and fourth hypotheses will be approached. The second hypothesis stated that training at CP would lead to improvements in LT-, $\dot{V}O_{2peak}$ - and economy-based parameters. Again relating to specificity, the fourth hypothesis predicted that the LT and $\dot{V}O_{2peak}$ parameters would respond more markedly following training below CP and intermittently around CP, respectively. These LT- and RAMP-derived results will be presented in turn. The final comparison reported within the current section will document the mitochondrial enzyme responses to the three training interventions.

*Overall responses*

Pre- to post-training responses have been expressed as a percent change and are displayed in table 9.12. There were no significant differences between any of the changes in physiological variables for any of the training groups ($P > 0.05$). In addition to the measures in table 9.12, body mass was unchanged for all groups from pre- to post-training (73.5 to 72.8, 74.6 to 74.9 and 70.2 to 70.0 kg for <CP, CP and $CP_{INT}$ groups, respectively; $P > 0.05$).

Table 9.12: Mean ± SEM percent changes from pre- to post-training for the three training groups (<CP, CP and $CP_{INT}$)

| | <CP | CP | $CP_{INT}$ |
|---|---|---|---|
| MMP (W) | 10 ± 1 % | 14 ± 1 % | 14 ± 2 % |
| $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$) | 8 ± 1 % | 9 ± 2 % | 12 ± 2 % |
| Economy (mL·min$^{-1}$·W$^{-1}$) | -12 ± 3 % | -8 ± 4 % | -11 ± 4 % |
| $HR_{peak}$ (beats·min$^{-1}$) | -3 ± 2 % | -3 ± 1 % | -3 ± 2 % |
| P-LT (W) | 34 ± 9 % | 27 ± 7 % | 21 ± 9 % |
| P-LT (% of MMP) | 22 ± 8 % | 12 ± 7 % | 6 ± 8 % |
| $\dot{V}O_2$ -LT (mL·kg$^{-1}$·min$^{-1}$) | 17 ± 5 % | 19 ± 6 % | 22 ± 12 % |
| $\dot{V}O_2$ -LT (% of $\dot{V}O_{2peak}$) | 9 ± 5 % | 11 ± 6 % | 13 ± 10 % |
| CP (W) | 12 ± 3 % | 19 ± 2 % | 12 ± 2 % |
| CP (% of MMP) | 2 ± 2 % | 4 ± 2 % | -1 ± 3 % |
| $\dot{V}O_2$ -$CP_{est}$ (mL·kg$^{-1}$·min$^{-1}$) | 5 ± 3 % | 6 ± 4 % | 6 ± 4 % |
| $\dot{V}O_2$ -$CP_{est}$ (% of $\dot{V}O_{2peak}$) | -3 ± 3 % | -2 ± 2 % | -1 ± 4 % |

MMP: maximal minute power; $HR_{peak}$: peak heart rate; P-LT: power output at lactate threshold; $\dot{V}O_2$ -LT: $\dot{V}O_2$ at lactate threshold; CP: Critical Power; $\dot{V}O_2$ -$CP_{est}$: estimated $\dot{V}O_2$ at CP
No significant differences between training groups: P > 0.05

*Critical Power modelling*

Post-training $TTE_{short}$, $TTE_{med}$ and $TTE_{long}$ data were systematically shorter post-training compared with pre-training (P < 0.05) but the post-training durations did not differ between training groups (P > 0.05; table 9.13). Moreover, average trial durations remained within acceptable ranges for CP determination (i.e., 3 – 15 min). The post-training peak HR values attained at the end of $TTE_{short}$, $TTE_{med}$ and $TTE_{long}$ were not different (96 ± 1, 96 ± 0 and 96 ± 0 % of $HR_{peak}$, respectively; P = 0.784) and did not differ from the pre-training values (P = 0.378).

Table 9.13: Mean ± SEM durations (s) for the shortest ($TTE_{short}$), medium ($TTE_{med}$) and longest ($TTE_{long}$) time to exhaustion trials used for post-training Critical Power determination

| | $TTE_{short}$ | $TTE_{med}$ | $TTE_{long}$ |
|---|---|---|---|
| <CP | 181 ± 12 | 343 ± 19 | 641 ± 45 |
| CP | 186 ± 13 | 414 ± 24 | 783 ± 35 |
| $CP_{INT}$ | 190 ± 13 | 416 ± 23 | 737 ± 39 |

No significant differences between training groups: P > 0.05

*Performance data*

Time to exhaustion at the pre-training MMP ($TTE_{preMMP}$) was included in the test battery both pre- and post-training and time to exhaustion at the post-training MMP ($TTE_{100\%MMP}$) was also measured post-training. The comparable TTE and TWD data are displayed in table 9.14. It can be seen from the first two data columns that for the same absolute power output (i.e., pre-training MMP), TTE was significantly greater post training. This reflects an improvement in exercise performance.

Table 9.14: Comparisons between time to exhaustion (s) at the pre-training MMP ($TTE_{preMMP}$) and at 100 % of MMP ($TTE_{100\%MMP}$) and total work done (kJ) at the pre-training MMP ($TWD_{preMMP}$) and at 100 % of MMP ($TWD_{100\%MMP}$)

| | $TTE_{preMMP}$ | | $TTE_{100\%MMP}$ | $TWD_{preMMP}$ | | $TWD_{100\%MMP}$ |
|---|---|---|---|---|---|---|
| | Pre-training | Post-training | Post-training | Pre-training | Post-training | Post-training |
| <CP | 209 ± 11 | 297 ± 16** | 179 ± 12* | 58 ± 5 | 81 ± 6** | 54 ± 5 |
| CP | 208 ± 14 | 366 ± 39** | 186 ± 13* | 59 ± 7 | 99 ± 11** | 59 ± 6 |
| $CP_{INT}$ | 216 ± 14 | 377 ± 51** | 193 ± 14* | 56 ± 5 | 92 ± 10** | 56 ± 5 |

Significantly different from pre-training: * $P < 0.05$, ** $P < 0.001$

*Critical Power*

Critical power increased significantly for all groups following training ($P < 0.001$), with post-training values of 209 ± 12, 216 ± 11 and 195 ± 12 W for <CP, CP and $CP_{INT}$ groups, respectively (figure 9.5*a*). However, there were no interaction effects between groups ($P = 0.158$). No changes in CP were evident when expressed as a % of MMP ($P = 0.415$), with post-training values of 70 ± 1, 70 ± 1 and 68 ± 2 W for <CP, CP and $CP_{INT}$ groups, respectively. The $\dot{V}O_2$ -$CP_{est}$ expressed in mL·kg$^{-1}$·min$^{-1}$ increased with training ($P = 0.019$), with post-training values of 36.4 ± 1.6, 35.8 ± 1.8 and 35.7 ± 2.6 for <CP, CP and $CP_{INT}$ groups, respectively (figure 9.5*b*). Again there were no interaction effects between groups ($P = 0.972$). Finally there were no differences when $\dot{V}O_2$ -$CP_{est}$ was expressed as a % of $\dot{V}O_{2peak}$ ($P = 0.236$), with post-training values of 70 ± 2, 69 ± 2 and 72 ± 3 for <CP, CP and $CP_{INT}$ groups, respectively (figure 9.5*c*).
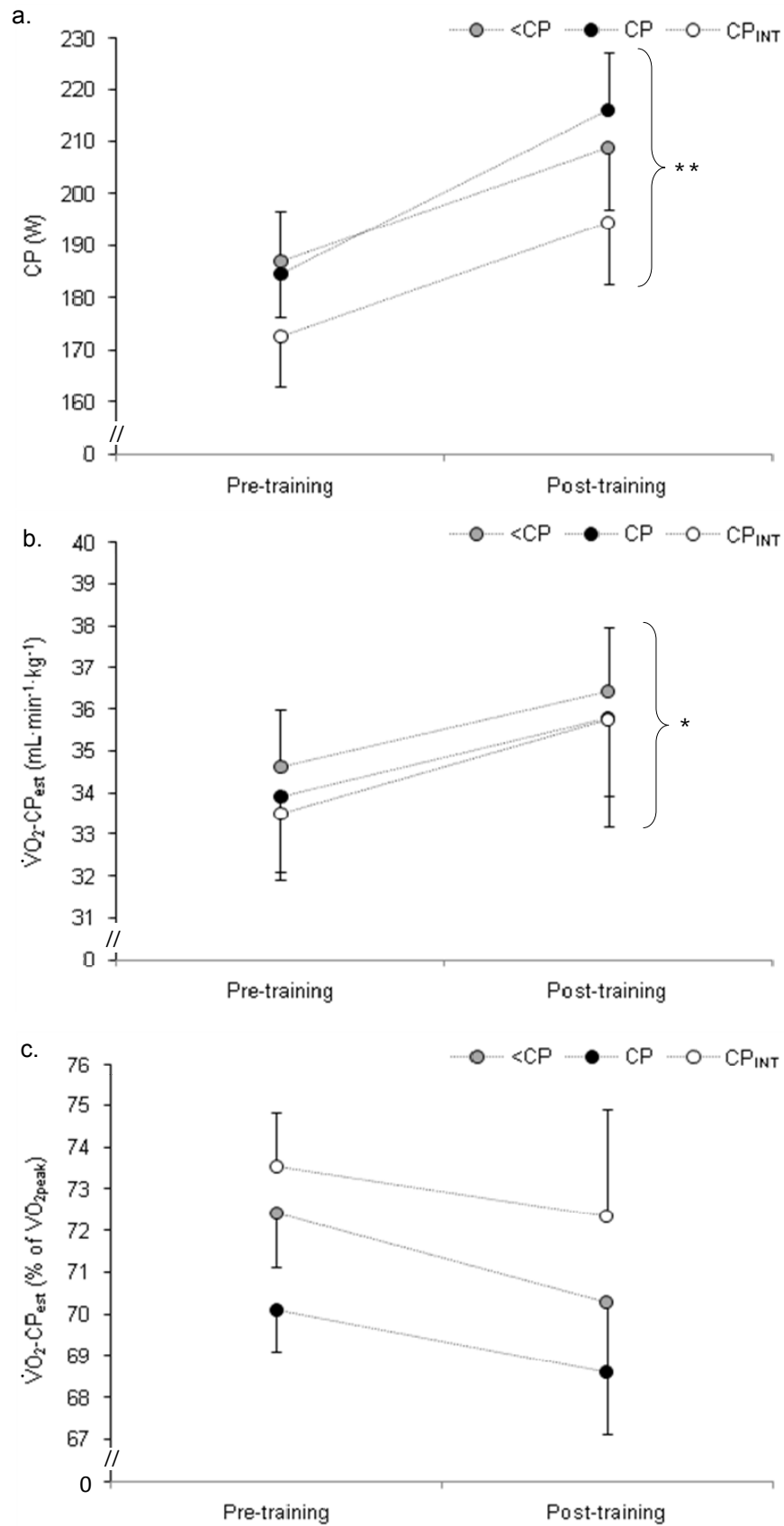
Figure 9.5: Pre- and post-training (a) Critical Power in W, (b) estimated $\dot{V}O_2$ at Critical Power ($\dot{V}O_2$ -$CP_{est}$) in mL·kg$^{-1}$·min$^{-1}$ and (c) $\dot{V}O_2$ -$CP_{est}$ as a % of $\dot{V}O_{2peak}$
Significantly different from pre-training: ** P < 0.001; * P < 0.05

*Lactate threshold*

Post training P-LT values were 116 ± 9, 123 ± 13 and 96 ± 9 W for the <CP, CP and CP$_{INT}$ groups, respectively, which reflected an increase following training for all three groups (P < 0.001) without any significant interaction effects (P = 0.441; figure 9.6*a*). Unlike CP, P-LT expressed as a % of MMP also increased following training (P = 0.009), with post-training values of 39 ± 2, 39 ± 3 and 33 ± 2 W for <CP, CP and CP$_{INT}$ groups, respectively. There were no interaction effects between training groups (P = 0.390). The $\dot{V}O_2$ -LT expressed in mL·kg$^{-1}$·min$^{-1}$ increased with training for all groups (P < 0.001), with post-training values of 24.9 ± 1.2, 26.5 ± 2.1 and 22.6 ± 2.1 for <CP, CP and CP$_{INT}$ groups, respectively, and no interaction effects between groups (P = 0.920; figure 9.6*b*). Finally, $\dot{V}O_2$ -LT expressed as a % of $\dot{V}O_{2peak}$ increased (P = 0.035), with post-training values of 48 ± 2, 51 ± 3 and 46 ± 3 for <CP, CP and CP$_{INT}$ groups, respectively (figure 9.6*c*). There were no interaction effects between training groups (P = 0.940).
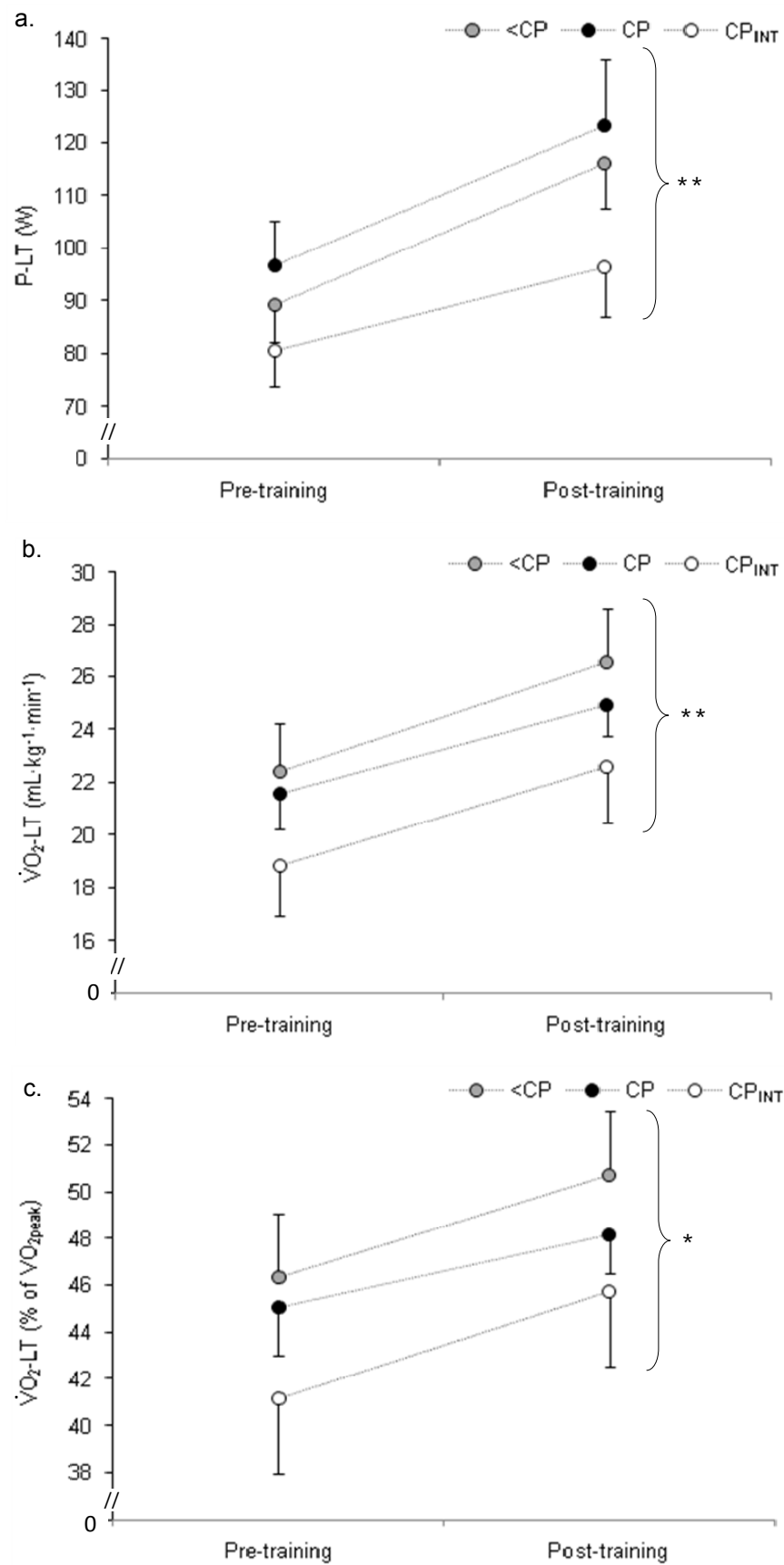
Figure 9.6: Pre- and post-training (a) power at lactate threshold (P-LT) in W, (b) $\dot{V}O_2$ at lactate threshold ($\dot{V}O_2$-LT) in mL·kg$^{-1}$·min$^{-1}$ and (c) $\dot{V}O_2$-LT as a % of $\dot{V}O_{2peak}$
Significantly different from pre-training: ** $P < 0.001$; * $P < 0.05$

*Incremental ramp test*

A typical pre- to post-training change in the $\dot{V}O_2$ -power output relationship obtained during the RAMP is displayed in figure 9.7. Economy (represented by the gradient of the relationship) improved for all groups ($P < 0.001$; figure 9.8) and no interaction effects were identified between groups ($P = 0.783$).

Post-training MMP and $\dot{V}O_{2peak}$ values for the <CP, CP and $CP_{INT}$ groups were $298 \pm 16$, $309 \pm 14$ and $286 \pm 14$ W and $48.5 \pm 2.1$, $48.1 \pm 2.3$ and $45.0 \pm 1.7$ mL·kg$^{-1}$·min$^{-1}$, respectively. These values reflected significant changes from pre- to post-training ($P < 0.05$; figure 9.9) with no significant interaction effects between training groups ($P > 0.05$).

The $HR_{peak}$ was significantly lower post-training for all groups ($196 \pm 2$, $190 \pm 2$ and $190 \pm 2$ beats·min$^{-1}$ for <CP, CP and $CP_{INT}$ groups) compared with pre-training values ($P = 0.005$) and no significant interaction effects were identified between groups ($P = 0.979$).

*Muscle enzyme content*

The pre- and post-training CS, SDH and ATP synthase content data for the three training groups are displayed in figure 9.10. The CS content was unchanged from pre- to post-training ($P = 0.783$) while changes in SDH and ATP synthase were both significant ($P < 0.05$). There were no interaction effects between groups ($P > 0.05$).
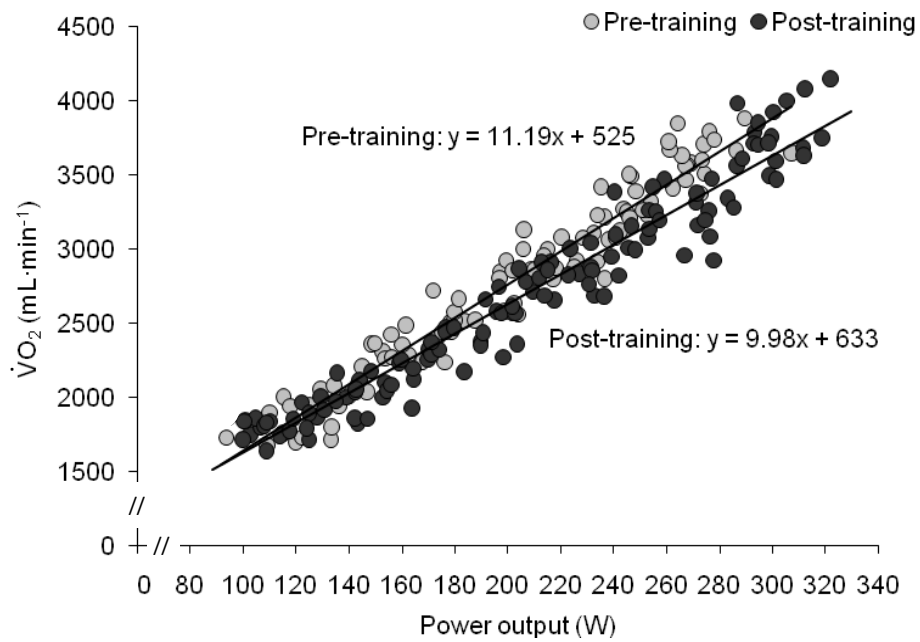
Figure 9.7: Typical pre- and post- training $\dot{V}O_2$ -power output profiles for one individual
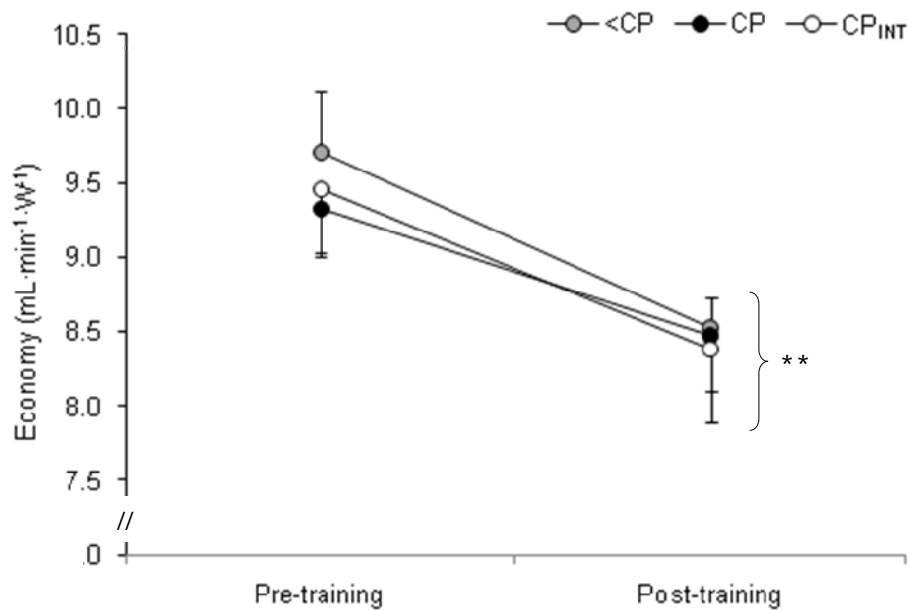


Figure 9.8: Pre- and post-training economy ($mL \cdot min^{-1} \cdot W^{-1}$) for the three training groups
Significantly different from pre-training: ** $P < 0.001$
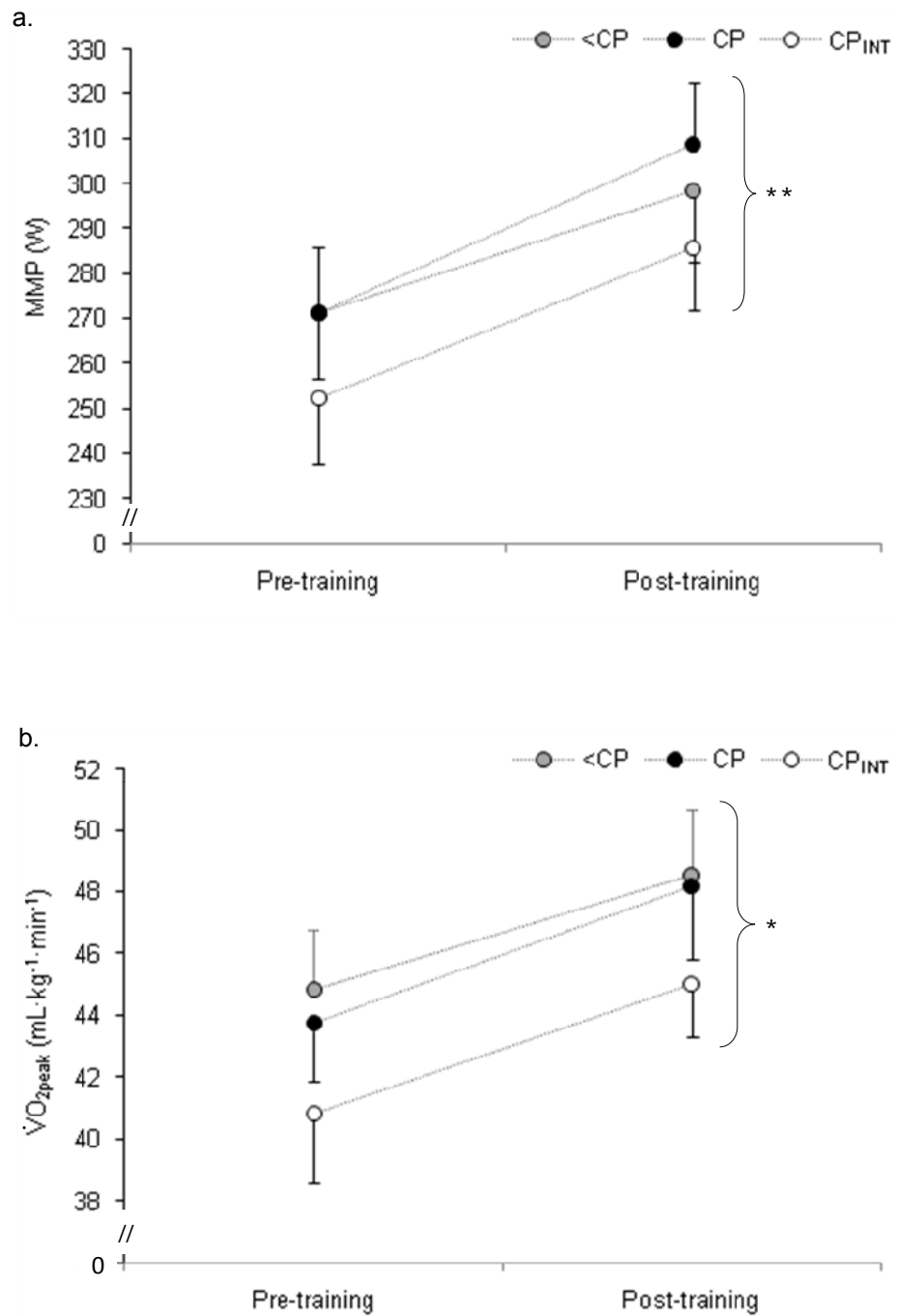
Figure 9.9: Pre- and post-training (a) maximal minute power (MMP), and (b) V̇O2peak
Significantly different from pre-training: ** P < 0.001, * P < 0.05
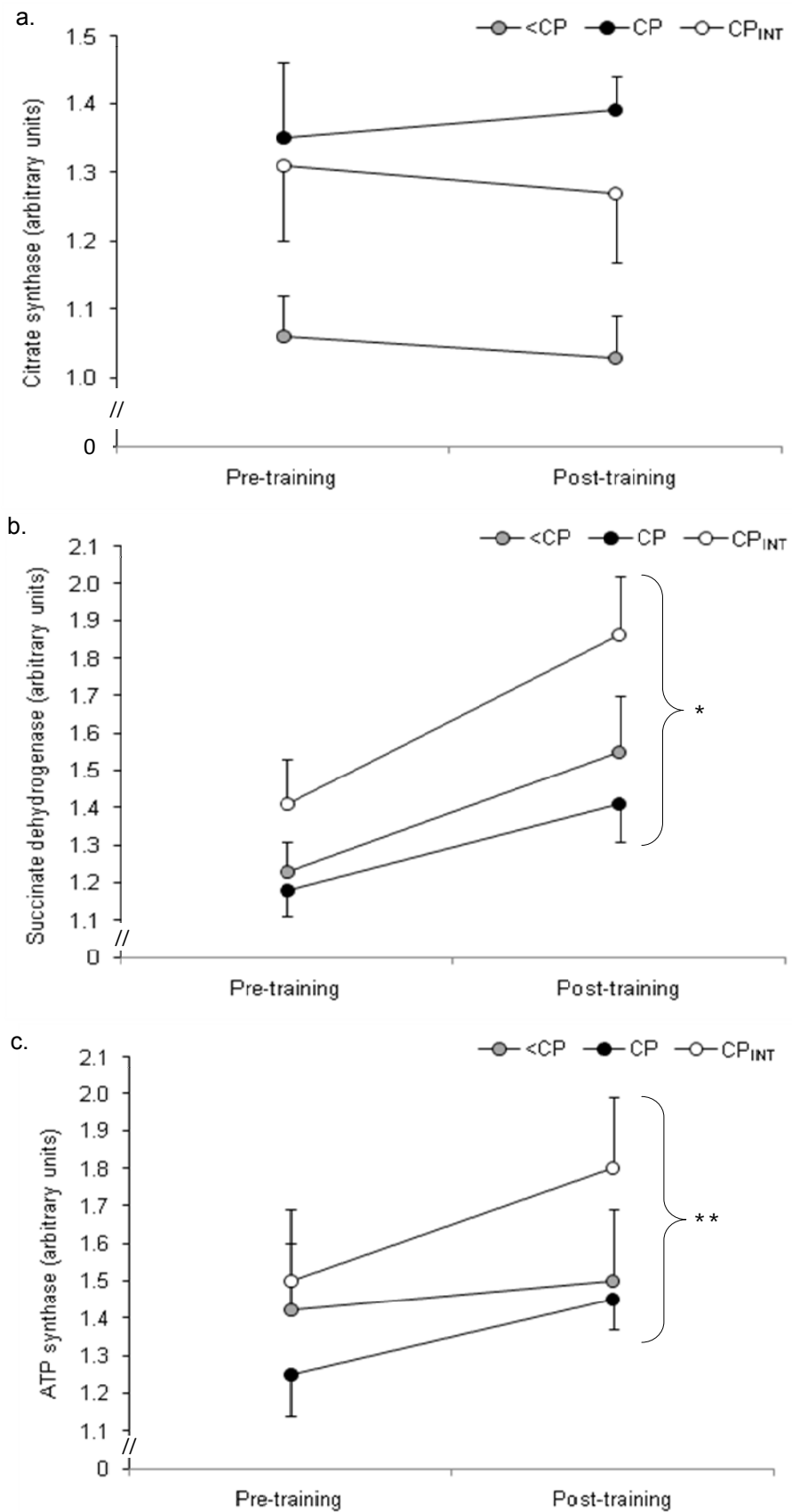
Figure 9.10: Pre- and post-training (a) citrate synthase, (b) succinate dehydrogenase and (c) ATP synthase content (arbitrary units)
Significantly different from pre-training: ** P < 0.001, * P < 0.05

## 9.5) Discussion

### 9.5.1) Overview of results

The purpose of the present study was to investigate the efficacy of three different CP-based training interventions on improving aerobic fitness. The three interventions involved three training sessions per week for six weeks and TWD was matched between the training groups. An overload progression was incorporated into the training programme by increasing TWD by 5 % after sessions 6, 10 and 14 (of 18), in order to maintain the training stimulus as fitness improved. While it is acknowledged that individual fitness adaptations would have occurred at different rates, standardised overload progressions were necessary to compare group responses and have previously been used within similar training intervention studies (Carter *et al.*, 1999; Daussin *et al.*, 2007; Duffield *et al.*, 2006; Edge *et al.*, 2006; Edge *et al.*, 2005; Tabata *et al.*, 1996).

The two specific primary aims of the present study were (i) to investigate the sensitivity of CP to aerobic training and (ii) to assess the effect of training at CP on other markers of aerobic fitness. The main findings showed that CP responded positively to all three aerobic training interventions (which will be discussed further in section 9.5.2) and that training at CP led to increases in LT, $\dot{V}O_{2peak}$, economy and muscle measures (which will be discussed further in section 9.5.3). These findings support the two main experimental hypotheses, confirming that CP is sensitive to aerobic training and is an effective training intensity for improving aerobic fitness. With training at CP involving significantly shorter-duration training sessions compared with training below and intermittently around CP (for the same TWD), the current study shows that CP as a training intensity provides "more bang for your buck" in terms of fitness gains per time spent exercising.

In the methods section (9.3.6) it was reported that the CP group would train for $23.2 \pm 0.7$ min, but it was outlined in the results section (9.4.2) that not all of the CP group were able to complete all of their training sessions, despite strong verbal encouragement, and the actual training time was only $22.2 \pm 0.7$ min. This was due to

the training intensity proving too high for seven of the individuals to maintain on some occasions, a response that has been reported previously during training at CP (Jenkins & Quigley, 1992). Given the wide range of exhaustion times highlighted in chapter 7 for exercise at CP it is unsurprising that the sessions were unsustainable for some individuals. The LOW and MOD groups in chapter 7, for example, had the most similar CP estimates to the CP group in the current study (175 ± 10, 211 ± 10 and 184 ± 12 W for the LOW, MOD and CP groups, respectively) and 6 out of the 17 participants in chapter 7 were unable to maintain exercise at CP for 23.2 min. The difficulty of completing the required work at CP may have been augmented further in the current training study due to the cumulative effect of participants having to repeat training sessions three times per week over six consecutive weeks. While exercise at CP was not always sustainable for a duration equivalent to 30 min at LT in terms of TWD, however, the adaptations following training at CP did not appear to be compromised by slight reductions in TWD.

The $HR_{end}$ data attained during training may help to explain the more time-concentrated adaptations experienced by the CP and $CP_{INT}$ groups. That is, the increased cardiovascular strain reflected by higher $HR_{end}$ values in the CP and $CP_{INT}$ groups, compared with the <CP group, may have increased the rate of central adaptations (e.g., increased left ventricular chamber volume and wall thickness, leading to increased SV and $\dot{Q}_{max}$). The similar aerobic fitness improvements for all three groups would then be attributable to the matched TWD (rather than exercise time) between training groups, which would have resulted in similar total cardiovascular strain and central adaptations. Although not a focus of the present study, it may be that the total heart beat demand (i.e., the area under the HR response curve) is an important determinant of adaptation to aerobic exercise. This notion was introduced some years ago with respect to training loads (Banister *et al.*, 1975), but requires further research in the context of training at and around CP.

The $\dot{V}O_2$-SC data presented in section 9.4.2 and figure 9.4 show that, although the differences between groups during week 3 were not significant, there was a strong tendency for the <CP group to demonstrate lower $\dot{V}O_2$-SC values than the other two groups. This tendency was strengthened at the end of the fourth overload progression,

during week 6, when the $\dot{V}O_2$-SC was significantly lower for the <CP group compared with the CP group. The greater increase in the aerobic demand from week 3 to week 6 for the CP group (illustrated by a steeper gradient on figure 9.4 for the CP group) may be due to the compounded effect of the 5 % overload progressions. That is, [CP x 1.05] presents the participant with a greater increase in absolute workload compared with [<CP x 1.05] and [CP x $1.05^3$] augments this difference when compared with [<CP x $1.05^3$]. So, while the training intensity for the <CP group may have remained around the boundary of moderate- to heavy-intensity exercise throughout the overload progressions (i.e., as aerobic fitness improved), individuals in the CP group may have shifted to the right on the exercise-intensity domain continuum, which would result in a significantly greater $\dot{V}O_2$-SC response. With the $\dot{V}O_2$-SC a manifestation of progressive muscle recruitment during exercise above LT (Endo *et al.*, 2007), it is possible that greater muscle activation explains the increase in the CP group. However, this possibility remains to be investigated. The $\dot{V}O_2$-SC data for the $CP_{INT}$ group has intentionally not been discussed in detail as the exercise-intensity domains and the development of a $\dot{V}O_2$-SC are only valid for constant-load exercise (Jones *et al.*, 2009), so the data for the $CP_{INT}$ group would be incomparable.

Performance was assessed in the present study using standardised CP determination trials pre- and post-training. The exhaustive trials at the pre-training MMP (i.e., a standardised load) showed that both TTE and TWD increased significantly after the six-week training intervention for all groups (table 9.14). This demonstrates an increased capacity to sustain exercise at a fixed power output around the upper boundary of the severe exercise-intensity domain, assuming MMP can be associated with this boundary. Although there was no significant interaction effect between groups (P = 0.324), $TTE_{preMMP}$ tended to improve to a greater extent in the CP and $CP_{INT}$ groups (i.e., by 159 ± 41 and 161 ± 49 s, respectively, versus 88 ± 20 s in the <CP group), which may be related to the tendency for greater improvements in MMP in the CP and $CP_{INT}$ groups (table 9.12). Exercising at a lower % of pre-training MMP would presumably be more sustainable than exercising at a higher % of pre-training MMP, due to reduced relative $O_2$ delivery and consumption needs at the original MMP. Although monitoring exercise performance was not an original focus of the current training study, these results provide original evidence that training

below, at and intermittently around CP leads to significant improvements in performance around the boundary between heavy- and severe-intensity exercise, which is an area worthy of further research.

*9.5.2) Effect of aerobic training on Critical Power*

The current study supports the first hypothesis stated in section 9.1, i.e., that CP would increase following each of the three training interventions. This confirms previous reports that CP is sensitive to aerobic training and supports the validity of CP as a marker of aerobic fitness. The observed improvements of 12 – 19 % are consistent with the only other study that appears to have measured changes in CP following six weeks of aerobic-based training (Gaesser & Wilson, 1988). In their study Gaesser and Wilson (1988) used two training interventions, continuous training below CP and interval training above CP (similar to the <CP and CP$_{INT}$ groups used in the present study) and reported increases in CP of 13 and 15 %, respectively.

The third hypothesis in section 9.1 related to the specificity of training and stated that training at CP would lead to greater improvements in CP compared with training below or intermittently around CP. Despite a strong tendency for the mean results to support this prediction (i.e., a 19 % increase in CP for the CP group versus 12 % increases for the two other groups), there was no significant interaction effect between groups for the changes in CP. This lack of significance may be due to the variable responses within each group, with CP increasing by 0 – 33, 2 – 36 and 0 – 26 % for individuals within the <CP, CP and CP$_{INT}$ groups, respectively. A closer look at the individual data, which is displayed in table 9.15, shows that only two of the 14 participants in the <CP group increased their CP by more than 19 % (i.e., the average of the CP group), and their responses were considerably higher than the rest of the <CP group (32 and 33 %, shaded grey). In addition, only four of the 14 participants in the CP$_{INT}$ group increased their CP by more than 19 % (also shaded grey). These observations suggest that the <CP and CP$_{INT}$ groups may have contained "responders" (i.e., individuals who adapted to the exercise stimulus to a greater degree), which is a concept that has previously been recognised within training programmes (Chapman *et al.*, 1998; Fritz *et al.*, 2006). The "responders" in the current example, though, do not appear to be characterised by greater improvements in other aerobic fitness variables,

as the correlations between the percentage changes from pre- to post-training were not significant between CP and LT, $\dot{V}O_{2peak}$ or economy (r < 0.18, P > 0.05).  Neither do higher training intensities explain the greater responses in CP as training workloads were not notably different for the "responders" in the <CP or $CP_{INT}$ groups compared with their training group counterparts.  Further focused research would help to identify the patterns underlying enhanced CP responses in some individuals following training below and intermittently around CP.

Table 9.15: Individual percent changes in Critical Power (in order of magnitude) for the three training groups

| Participant | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| <CP | 0 | 3 | 5 | 5 | 8 | 8 | 9 | 9 | 12 | 12 | 15 | 16 | 32 | 33 | |
| CP | 2 | 7 | 11 | 14 | 15 | 15 | 16 | 17 | 19 | 19 | 21 | 22 | 31 | 36 | 36 |
| $CP_{INT}$ | 0 | 1 | 1 | 9 | 10 | 11 | 11 | 13 | 14 | 18 | 20 | 20 | 20 | 26 | |

In contrast to the "responders" in the <CP and $CP_{INT}$ groups, three "non-responders" may be identified in the CP group as those whose CP increased by less than the 12 % average of the <CP and $CP_{INT}$ groups (again shaded in grey in table 9.15).  These individuals were perhaps more notable as all three were in the sub-group of CP group participants who failed to complete all of their prescribed training at CP.  In fact, five of the seven individuals who failed to complete all of their training at CP recorded increases in CP lower than the training-group average of 19 %.  Therefore, contrary to the previous statement in section 9.5.1, that the adaptations following training at CP do not appear to be compromised by slight reductions in TWD, this suggests that greater increases in CP may, in fact, be related to the completion of the prescribed TWD at CP.  Indeed, data from the current study show that the mean ± SEM increase in CP for the eight participants who completed all of their training at CP was 24 ± 3 %, which is considerably higher than the 12 % increases recorded for the <CP and $CP_{INT}$ groups.  While results from the current study do not wholly support the principle of training specificity for improving CP, there is sufficient evidence to suggest that a completed programme of training at CP may be more effective for improving CP compared with training below or intermittently around CP.

*9.5.3) Effect of training at and around Critical Power on lactate threshold, $\dot{V}O_{2peak}$, economy and muscle measures*

The second main hypothesis in section 9.1 stated that training at CP would lead to improvements in LT, $\dot{V}O_{2peak}$, economy and muscle enzyme content. While no previous research has strictly used CP as a training intensity, this hypothesis was based on previous research showing improvements across a similar range of aerobic fitness parameters following training at relative work rates that would approximate CP. Results from the present study support the hypothesis as significant improvements were recorded for P-LT (in W and % of MMP), $\dot{V}O_2$-LT (in mL·kg$^{-1}$·min$^{-1}$ and % of $\dot{V}O_{2peak}$), economy (reductions in mL·min$^{-1}$·W$^{-1}$), MMP (in W), $\dot{V}O_{2peak}$ (in mL·kg$^{-1}$·min$^{-1}$) and SDH and ATP synthase contents.

These results are comparable to a previous study that measured the effects of training at MLSS on aerobic fitness markers (Philp *et al.*, 2008). Using a population of young, healthy, mixed-sex participants, Philp *et al.* (2008) found that training at MLSS twice a week for eight weeks significantly improved running velocity at LT, or v-LT (km·h$^{-1}$) by 7 %, $\dot{V}O_{2max}$ (mL·kg$^{-1}$·min$^{-1}$) by 10 % and v-$\dot{V}O_{2max}$ (km·h$^{-1}$) by 5 %. These markers may be likened to P-LT (W), $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$) and MMP (W) reported in the present study, respectively. Unlike the present study, which showed an 11 % increase in relative $\dot{V}O_2$-LT$_{est}$, Philp *et al.* (2008) reported a 3 % decrease in relative LT. This suggests that training at CP is more effective than training at MLSS (i.e., a lower exercise intensity) in augmenting LT at a faster rate than $\dot{V}O_{2peak}$, which may be due to enhanced peripheral adaptations with CP training. Alternatively, methodological differences between the two studies (e.g., cycling versus running, initial fitness status of participants and/or frequency of training) may explain the different results. Nevertheless, both sets of data show that continuous training between LT and $\dot{V}O_{2peak}$ is effective in enhancing both LT- and $\dot{V}O_{2peak}$-based fitness parameters. In addition, training at CP improves relative LT. This suggests that CP training may lead to improved aerobic endurance, a possibility that requires further research.

The fourth and final hypothesis in section 9.1 related to the specificity of training and stated that the LT and $\dot{V}O_{2peak}$ parameters would respond more markedly following training below CP and intermittently around CP, respectively. However, the lack of any significant differences between the parameters reported in table 9.12, and the lack of any interaction effects between training groups, do not support this hypothesis. Similar findings have been reported by Poole *et al.* (1985), who showed $\dot{V}O_{2max}$ to increase following training at ~ 50 % of $\dot{V}O_{2max}$, ~ 70 % of $\dot{V}O_{2max}$ and intermittently at ~ 105 % of $\dot{V}O_{2max}$ (with no differences in $\dot{V}O_{2max}$ adaptations between groups). These intensities used by Poole *et al.* (1985) were very similar to those used in the present study for the <CP, CP and CP$_{INT}$ groups (~ 53, ~ 68 and ~ 103 % of MMP, respectively). Philp *et al.* (2008) also demonstrated comparable increases in $\dot{V}O_{2max}$ following training at MLSS versus intermittent training 0.5 km·h$^{-1}$ above and below MLSS and Edge *et al.* (2005) reported similar increases in $\dot{V}O_{2peak}$ following moderate-intensity continuous and high-intensity interval training at 80 − 95 and 120 − 140 % of P-LT, respectively. These studies, combined with results from the current study, fail to support the notion that $\dot{V}O_{2peak}$ increases to a greater extent after training at an intensity closer to $\dot{V}O_{2peak}$.

Despite these findings, there is a body of evidence showing that progressively higher-intensity training interventions induce progressively greater changes to $\dot{V}O_{2max}$ (Gaesser & Wilson, 1988; Jenkins & Quigley, 1992). Moreover, $\dot{V}O_{2max}$ has been shown to increase following high-intensity intermittent training using work rates similar to the CP$_{INT}$ group in the current study, but not following work-matched lower-intensity continuous training interventions similar to the <CP and CP groups in the current study (Daussin *et al.*, 2007; Gormley *et al.*, 2008; Helgerud *et al.*, 2007). The reason that some studies demonstrate a training-intensity − response-type relationship for $\dot{V}O_{2peak}$ does not seem to be attributable to the training status of the participants, training frequency or the intervention duration, as these were all similar between studies. The mechanistic explanations offered by Daussin *et al.* (2007) and Helgerud *et al.* (2007), i.e., that central adaptations (increases in SV and $\dot{Q}_{max}$) occur during high-intensity intermittent training but not during lower-intensity continuous training, are not supported in the current study. Furthermore, no differences in

peripheral adaptations were identified between groups, as reflected by the similarity of changes in the CS, SDH and ATP synthase content.

It is possible that the training groups were not differentiated to a large enough degree in the current study to induce significantly different central and peripheral responses over a six-week intervention period. For example, while the CP$_{INT}$ group were prescribed repeated bouts of high-intensity work, the average power output per training session (when combined with the low-intensity recovery bouts) was not different from the <CP group (mean power output values differed by only 4 W). In addition, the intermittent protocol required individuals to exercise continuously throughout each session and, as a result, the average total exercise duration was only 4.2 min shorter than for the <CP training group. Since previous intermittent protocols have used much higher training intensities and shorter exercise durations to bring about increases in $\dot{V}O_{2max}$ (Burgomaster *et al.*, 2008; Rodas *et al.*, 2000), it may be that more extreme group differences would have been required for a training-intensity – response relationship to have been observed.

*9.5.4) Summary*

The current training study has highlighted a number of novel observations relating to the practical use of CP as a marker of aerobic fitness and as a training intensity. The main findings were that:
- CP responded positively to all three aerobic training interventions (<CP, CP and CP$_{INT}$) and as such, is confirmed as being sensitive to aerobic exercise training;
- training at CP led to increases in LT, $\dot{V}O_{2peak}$, economy and muscle enzyme content and as such, is confirmed as an effective training intensity for improving aerobic fitness;
- while training at CP may not always be sustainable for the prescribed duration, average adaptations in aerobic fitness do not appear to be compromised;
- individual failure to complete all prescribed training at CP may inhibit the potential for enhanced improvements in CP, while completing all prescribed training at CP may allow for these enhanced improvements;

- training intensity was not related to the magnitude of change in absolute measures of LT or $\dot{V}O_{2peak}$;
- six weeks of CP-based training led to increases in performance (TTE and TWD at MMP);
- greater improvements in TTE at the pre-training MMP may be related to greater improvements in absolute MMP.

In conclusion, the findings from the present study have shown that work-matched training below CP, at CP and intermittently around CP three times per week for six weeks leads to similar improvements in aerobic-based physiological and performance parameters. This similarity in training responses may be attributable to the average training durations and power outputs differing by less than 8 min and 44 W, respectively. Despite these findings, the CP training group exercised for a significantly shorter period of time during each training session (and at a significantly higher average power output), which adds to the mounting evidence that more effort and less time spent exercising can lead to improvements in endurance capacity (Gibala & McGee, 2008).

# 10) General Discussion

The primary aim of this thesis was to investigate the application of the CP construct to endurance exercise, where endurance exercise was defined in chapter 1 as exercise predominantly reliant upon aerobic energy metabolism. This task was approached using practical methods, in order to allow real-world applications of CP to be developed. As outlined in section 5.3, the specific research aims were to ascertain whether the CP parameter may be applied:

(i) generically to groups with different aerobic fitness levels, in terms of the physiological characteristics of CP and the physiological responses to exercising at and around CP;

(ii) as a valid marker of aerobic fitness that is sensitive to training;

(iii) as an effective training intensity for improving aerobic fitness.

Before discussing the results of this thesis in the context of the original aims it is first worth re-visiting the process of CP modelling. A number of methodological issues were discussed throughout the literature review and subsequently within the experimental chapters. As such, section 10.1 aims to produce a revised set of CP-modelling guidelines based on existing and new evidence. Section 10.2 then presents an overview of the main experimental findings and sections 10.3 and 10.4 consider these findings in greater detail. The chapter will conclude with a section on future directions for research (10.5) and a final conclusion (10.6).

## 10.1) Guidelines for Critical Power modelling

A set of recommended guidelines for CP modelling were originally outlined in section 2.2.5. These guidelines will now be reviewed in light of the findings of this thesis and a new set of standardised methods for CP modelling using cycling exercise will be proposed.

*10.1.1) Model choice*

In chapter 2 a thorough review of the various methods for modelling CP was presented. The exponential and 3-parameter models were deemed inappropriate in applied settings for a number of reasons, including the limited range of exercise durations over which the resulting CP estimate applies, the poor reliability of the additional $P_{max}$ parameter and the difficulties for practitioners in deriving the CP parameter estimate. Based on ease of deriving a parameter estimate in practice, a linear model is more suitable than a non-linear model, which left the w-t and P-t$^{-1}$ models as best choices. It was suggested that the P-t$^{-1}$ model would be favourable over the w-t model as P reflects a direct measure while w is a composite of P and t.

The P-t$^{-1}$ model provided a straightforward method for deriving CP estimates throughout this series of investigations and unreported comparisons between the P-t$^{-1}$ and w-t models revealed similar CP estimates. For all participants used in chapter 7, for example, the CP estimate was only (mean ± SD) 2.1 ± 3.6 W higher when derived from the P-t$^{-1}$ versus the w-t model. This difference is consistent with previous research (Bull *et al.*, 2000; Gaesser *et al.*, 1995; Hill *et al.*, 2003; Housh *et al.*, 2001). The mean ± SD linear fit was slightly lower (by 0.011 ± 0.011) for the P-t$^{-1}$ versus the w-t model and the SEE was slightly higher (by 2.33 ± 1.60 W). Despite these differences, due to the ease of use and the direct measurement of P, this thesis supports the P-t$^{-1}$ model as the most appropriate method for deriving CP estimates in research and applied settings. This recommendation is delimited to environments where P can be fixed (i.e., imposed) and t measured. There may be circumstances where work done (or distance covered) would be fixed, but the guidelines presented in the current thesis do not apply to such circumstances.

*10.1.2) Familiarisation trials*

The recommendation that one or two familiarisation trials are required prior to data collection was not supported in chapter 6, as there was no decline in variation from the initial TTE trials (over a series of 10, repeated tests). Instead, it was suggested that a minimum of three data points are used when modelling CP and that an excellent linear fit (r > 0.97) to the P-t$^{-1}$ model is obtained. However, it is worth

acknowledging that the participants used in chapter 6 were familiar with an exercise laboratory environment, as well as cycle ergometry, and all were recreationally active. The need for familiarisation trials within sedentary populations or among individuals not accustomed to the exercise setting may be greater (Hopkins *et al.*, 2001). This possibility requires further investigation and until that time, it may be wise to follow previous advice (Bishop & Jenkins, 1995; McLellan *et al.*, 1995) by familiarising unaccustomed individuals prior to data collection for actual CP modelling. In the experimental studies in this thesis, familiarisation trials were used to gain preliminary information on individuals' TTE durations at standardised power outputs. This proved to be a valuable process when choosing work rates for subsequent data collection trials and further supports the use of some preliminary TTE trials.

*10.1.3) Number of trials*

Following the review of literature in section 2.2.1, three TTE trials were proposed as optimal for modelling CP. This suggestion was based on the need to balance the potential inaccuracies when using only two data points with the time and motivation issues associated with prescribing numerous trials (Hill, 1993). However, standardised use of only three trials is not supported by the data presented in this thesis. For example, 54 % of all participants tested in chapters 7 and 9 (i.e., 37 of the 68 participants in total) were required to complete a fourth CP determination trial in order to achieve a linear fit to the $P\text{-}t^{-1}$ relationship of r > 0.97. Therefore, it is suggested that three trials should initially be used and, if the model yields a linear fit of r < 0.97, a fourth trial should be conducted and included in the model. This process may reveal an outlying data point from one of the three initial trials, which the experimenter or coach may choose to discard.

*10.1.4) Duration of trials*

While the duration range of ~ 3 – 15 min for CP-determination trials is a fundamental characteristic of the CP construct, the additional restriction introduced in chapter 9 (i.e., that at least one TTE data point should lie within the time ranges 3 – 5, 7 – 10 and 12 – 15 min) may be an effective method to help strengthen the model. That is, ensuring an even spread of short-, medium- and long-duration trials would be

important for controlled experimental studies, applied physiological testing and fitness monitoring as the factors associated with fatigue (e.g., energy supply and/or depletion, metabolic disturbances, muscle recruitment, central nervous system and/or psychological factors) differ with varying exercise durations (Fitts, 1994). An even spread of short-, medium- and long-duration trials may also reduce any error in the CP estimate that may result from three long-duration trials, which were documented in chapter 6 to be highly variable. A theoretical example of this is displayed in figure 10.1 for one individual who cycles at 290, 250 and 230 W for 3.3, 7.9 and 13.9 min, respectively, during one set of CP determination trials (filled markers) and for 10.0, 12.3 and 14.8 min, respectively, during another set of CP determination trials (unfilled markers). Although the P and r vales are matched for this individual during the two sets of trials, the CP estimates (214 versus 103 W, respectively) are heavily affected by the spread of trial durations. Paradoxically, exercising for longer during the three fixed power trials (unfilled markers), which would intuitively signify a greater capacity for aerobic exercise, leads to a CP estimate less than half that of the model where matched power outputs elicited shorter exercise durations (filled markers). This theoretical scenario highlights a potential importance of spanning the full range of durations (i.e., 3 – 15 min) when deriving valid parameter estimates from the $P$-$t^{-1}$ model.
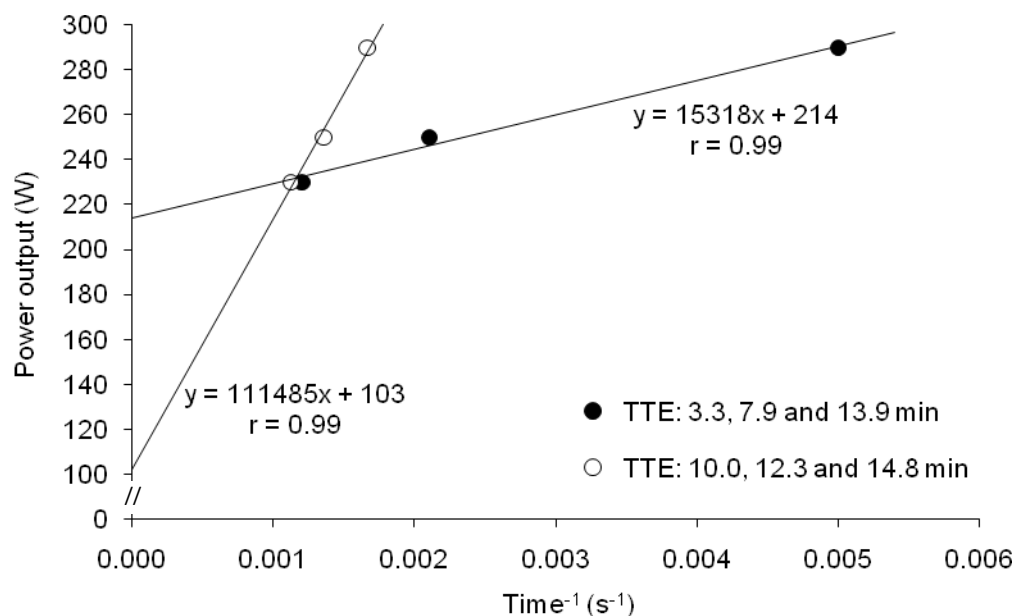


Figure 10.1: Two theoretical Critical Power estimates for the same individual using a full spread of time to exhaustion trials lasting 3 – 5, 7 – 10 and 12 – 15 min (black filled markers) and only long-duration trials lasting 10 – 15 min (unfilled markers)

Another precaution when monitoring trial duration was implied in section 8.3.1, where it was highlighted that not all participants in chapter 7 produced exercise durations that became progressively longer as exercise intensity decreased (i.e., from 105 to 100 to 95 % of CP). Although not directly related to the durations used in the CP determination process, this suggests that some individuals may, on occasion, exercise for longer at higher exercise intensities during CP-determination trials (perhaps due to motivation, learning effects, altered training status, etc.). This highlights the need to carefully control for any extraneous factors that could affect TTE during CP-determination trials by standardising the environmental conditions within the laboratory, the exercise equipment and the participant's nutritional, recovery and motivational states.

*10.1.5) Cycle ergometry*

The guidelines in chapter 2 incorporated recommendations specific to cycle ergometer work carried out in a laboratory. The SSC method, supported by previous authors to minimise fatigue and improve performance (Nesi *et al.*, 2004; Takaishi *et al.*, 1994; Vercruyssen *et al.*, 2001; Weissland *et al.*, 1997), was used in all experiments reported in this thesis and was deemed appropriate as it allowed individuals to feel comfortable and confident while cycling. Furthermore, although Green *et al.* (1995) showed no effect of cadence drop-off on CP estimates, terminating exercise when cadence dropped by > 5 revs·min$^{-1}$ on a second occasion was crucial in determining "exhaustion" in the studies within this thesis. With participants responding differently at the onset of fatigue it was important to have a clear, standardised procedure.

*10.1.6) Summary*

Given the collection of evidence discussed in sections 10.1 – 10.5 it is proposed that CP for cycling exercise is modelled using:
- the linear P-t$^{-1}$ relationship: $P = AWC \cdot t^{-1} + CP$
- preliminary TTE trials prior to data collection to familiarise unaccustomed exercisers and to improve the accuracy of exercise intensity prescription
- three or four TTE trials

- a linear fit of r > 0.97

- trials lasting 3 – 15 min with at least one TTE data point lying within the time ranges 3 – 5, 7 – 10 and 12 – 15 min

- a carefully controlled experimental environment and participant state

- an SSC that is consistent during all trials

- a reduction in cadence of > 5 revs·min$^{-1}$ to define exhaustion

## 10.2) An overview of the main experimental findings

As stated at the start of this chapter, the primary aim of this thesis was to investigate the application of the CP construct to endurance (or aerobic) exercise. Two main experimental studies were set up to achieve this. Firstly, the characteristics of CP and the responses to exercise at CP were examined in groups that were differentiated by $\dot{V}O_{2peak}$. Secondly, CP was used as a measure of aerobic fitness and as an intensity for training within a homogeneous group of active individuals. Based on group data, results showed that:

- CP as a marker of aerobic fitness is largely similar across groups that differ for $\dot{V}O_{2peak}$ (and CP), with the LT < CP < $\dot{V}O_{2peak}$ relationship persisting, irrespective of fitness status

- responses to exercise at and around CP are not different between groups that differ for $\dot{V}O_{2peak}$, although individual responses within groups are highly variable

- CP is sensitive to a range of aerobic training interventions, including low-intensity continuous, higher-intensity continuous and intermittent training

- CP can be used as a training intensity for improving aerobic fitness parameters and exercise performance

## 10.3) What does Critical Power *really* represent?

The three exercise-intensity domains (moderate, heavy and severe) defined by Gaesser and Poole (1996) were described in section 3.1 by distinct [La$^-$]$_{bl}$ and $\dot{V}O_2$ responses to constant-load exercise (figure 3.2; table 3.1). A diagrammatical representation of the exercise-intensity domains was initially displayed in figure 3.3,

with CP proposed as equivalent to LT and demarcating the moderate- and heavy-intensity domains. However, the review of literature led to a development of a revised model of the exercise-intensity domain continuum, which was illustrated in figure 3.5 and included an additional "very heavy" domain. Although discussed previously in the literature, the physiological definitions of the very heavy-intensity exercise domain and the associations with CP have been inconsistent (Endo *et al.*, 2007; Özyener *et al.*, 2003; Smith & Jones, 2001). With evidence suggesting that CP reflects an exercise intensity that is greater than MLSS (Dekerle *et al.*, 2003; McLellan & Cheung, 1992; Pringle & Jones, 2002), but not intense enough to elicit $\dot{V}O_{2max}$ (Baron *et al.*, 2005; Brickley *et al.*, 2002; Hill *et al.*, 2002; Hill & Smith, 1999; McLellan & Cheung, 1992; Overend *et al.*, 1992; Poole *et al.*, 1988; Poole *et al.*, 1990), CP was depicted in figure 3.5 as spanning the very heavy-intensity exercise domain. One purpose of this thesis was to better understand the controversy surrounding the physiological characteristics of CP.

Part 1 of chapter 7 showed that, irrespective of fitness group, CP reflects an exercise intensity that lies between LT and $\dot{V}O_{2peak}$. The data presented in part 2 of chapter 7 then showed that $\dot{V}O_2$ does not stabilise during exercise at CP and, moreover, for the LOW group the $\dot{V}O_2$ attained at the end of exercise at CP was not different from $\dot{V}O_{2peak}$. This was supported by the case study data in section 8.2.4, whereby the three LOW group individuals (i.e., those with a $\dot{V}O_{2peak} < 40$ mL·kg$^{-1}$·min$^{-1}$) characterised in tables 8.5 and 8.6 all elicited end-exercise $\dot{V}O_2$ values greater than 92 % of $\dot{V}O_{2peak}$ (figures 8.4*a* and 8.5*a*). These measures are within the 11 % daily variation range that can be expected for $\dot{V}O_{2peak}$ (Katch *et al.*, 1982). While these findings confirm that CP reflects non-steady state exercise, they also imply that CP may be reflective of severe-intensity exercise within low fitness individuals. This possibility has not been previously reported in the literature.

In addition to the non-steady $\dot{V}O_2$ response, $[La^-]_{bl}$ did not stabilise during exercise at CP. This supports the existing body of evidence that shows CP to lie beyond MLSS on the exercise-intensity domain continuum. Further evidence that CP exceeds MLSS was provided by the mean ± SD TTE data for exercise at CP. That is, TTE at CP was

25.0 ± 12.5 min for all 25 participants in chapter 7, which is considerably shorter than the TTE that has been previously reported by Baron *et al.* (2008) for exercise at MLSS (55.0 ± 8.5 min). The case study comparisons highlighted in section 8.2.4 showed the $[La^-]_{bl}$ responses during exercise at CP to be consistent, irrespective of absolute CP, as individuals with a high absolute CP experienced similar changes in $[La^-]_{bl}$ as those with a low absolute CP.

Based on the data presented in this thesis, therefore, figure 3.5 has been further revised and a new exercise-intensity domain continuum is presented in figure 10.2. The very heavy domain, characterising those exercise intensities too high to allow $[La^-]_{bl}$ to plateau but not intense enough to elicit $\dot{V}O_{2peak}$, has intentionally been depicted as narrower than the other domains. This is to represent the physiological sensitivity around CP, whereby reductions in the work rate of only 5 % below CP leads to $[La^-]_{bl}$ responses that reflect a steady state (among moderately fit individuals, at least). The range for CP has also been shown to overlap into the severe-intensity exercise domain, as this may be the case for low fitness individuals at least. An updated revised version of figure 3.4 is also proposed, in figure 10.3, to illustrate the average $[La^-]_{bl}$ response for exercise at CP in relation to other markers of aerobic fitness. The model is based on the $[La^-]_{bl}$ responses illustrated in figures 7.8*b*, 8.4*b* and 8.5*b*.
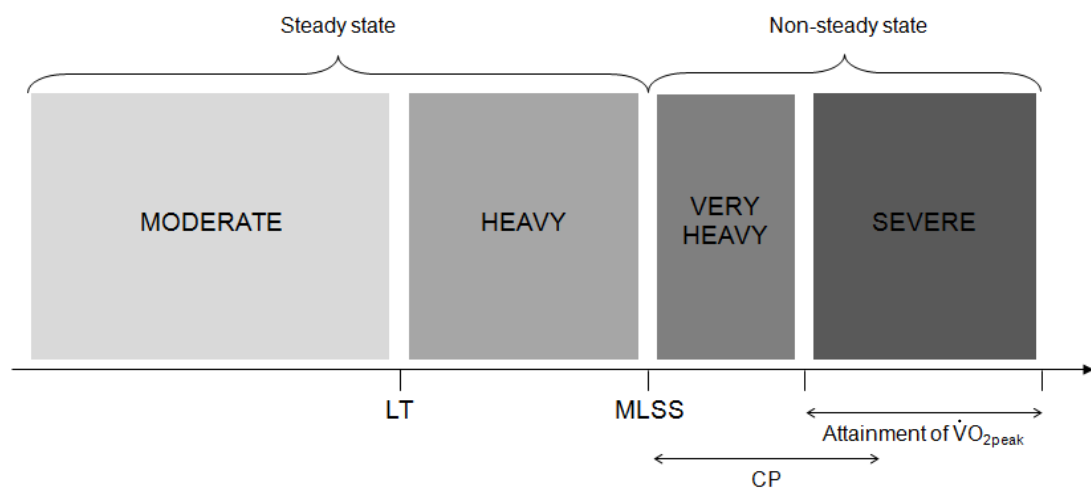


Figure 10.2: A new revised diagrammatical representation of the exercise-intensity domains characterised by lactate threshold (LT), maximal lactate steady state (MLSS), Critical Power (CP) and $\dot{V}O_{2peak}$
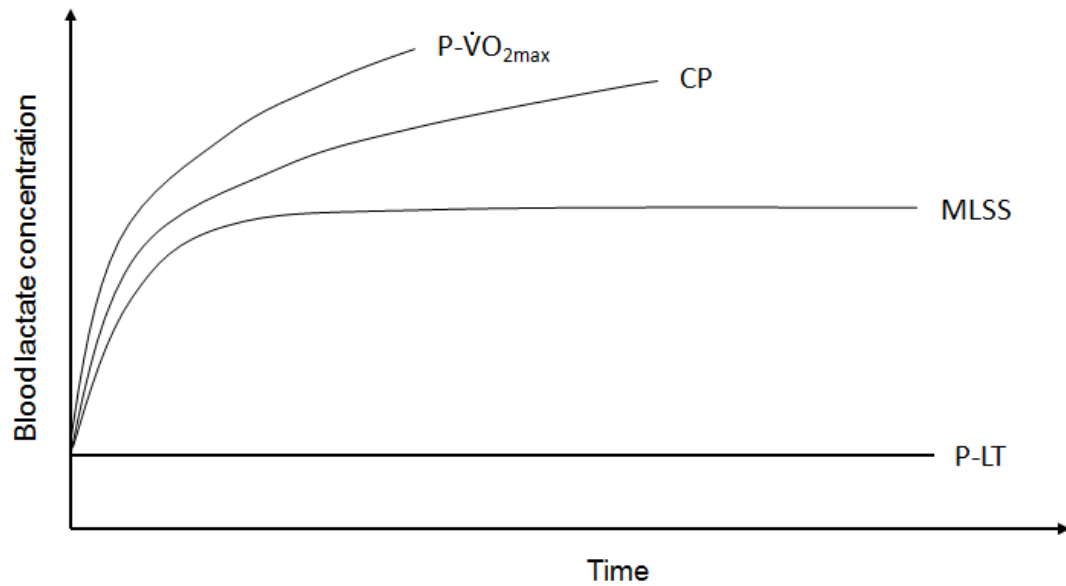
Figure 10.3: A new revised theoretical model of endurance represented by the blood lactate response to exercise at the power outputs associated with lactate threshold (P-LT), maximal lactate steady state (MLSS), $\dot{V}O_{2max}$ (P-$\dot{V}O_{2max}$) and Critical Power (CP)

Since sub-maximal, constant-load exercise to exhaustion requires motivation, concentration and a degree of pain tolerance, it is possible that psychological factors, which were not measured in this thesis, played an important role in the voluntary cessation of exercise at CP and, therefore, affected TTE. It is also theorised that ammonia accumulation in the brain during prolonged exercise can influence perceived exertion and influence central fatigue (Nybo, 2005), so it may be that individual differences in ammonia metabolism are related to shorter TTE durations. This is supported by Baron *et al.* (2008), who showed blood ammonia concentrations to increase during exercise to fatigue at MLSS with few other physiological parameters relating to the process. While a detailed analysis of fatigue theories is beyond the scope of this thesis, a better understanding of the causes of fatigue and exhaustion during exercise at CP would help scientists, athletes, coaches and practitioners in applying interventions (i.e., training programmes) for improving performance.

## 10.4) The application of Critical Power in training

The main objectives of the training study were to assess the sensitivity of CP to different aerobic training interventions and to determine whether CP may be used as an effective training intensity for improving aerobic fitness. Firstly, results showed

that the CP parameter is responsive to low-intensity continuous (<CP), higher-intensity continuous (CP) and intermittent ($CP_{INT}$) training. Furthermore, LT, $\dot{V}O_{2peak}$, economy and muscle enzyme content were all sensitive to training at CP, as well as to training below and intermittently around CP. However, the degree of change in the physiological parameters was not related to any of the specific training interventions, with no interaction effects observed between training groups for any of the measured responses. This may be related to the initial fitness levels of the participants used within the training study, who were all recreationally active but were not highly trained. Since non-highly trained individuals would have a greater potential for adaptations in aerobic fitness and performance markers compared with highly trained individuals, any demanding training stimulus (such as the three interventions used within chapter 9) would presumably lead to significant improvements across the range of aerobic measures. This is supported by previous studies that have recruited healthy but non-highly trained individuals and reported increases across a range of fitness markers (e.g., v-LT, $\dot{V}O_2$-LT, v-MLSS, MLSS, v-$\dot{V}O_{2max}$ and $\dot{V}O_{2max}$), but no interaction effects between different intensity interventions (Edge *et al.*, 2005; Philp *et al.*, 2008; Poole & Gaesser, 1985).

Despite there being no significant differences in the physiological responses to training at different exercise intensities, there was a tendency for CP to increase to a greater extent following training at CP and for $\dot{V}O_{2peak}$ to increase to a greater extent following the intermittent training intervention. This is shown in figure 10.4, which is a development of figure 4.2 and combines data from this thesis with previous data showing the effects of aerobic training on percent changes in CP and $\dot{V}O_{2peak}$. It may be speculated that if the CP and $CP_{INT}$ groups had exercised for as long as the <CP group (i.e., 30 min), rather than matching for TWD, then the effects on both CP and $\dot{V}O_{2peak}$ would have been greater for the CP and $CP_{INT}$ groups, respectively (represented by the filled black and unfilled markers). This possibility remains to be investigated using duration-matched interventions.
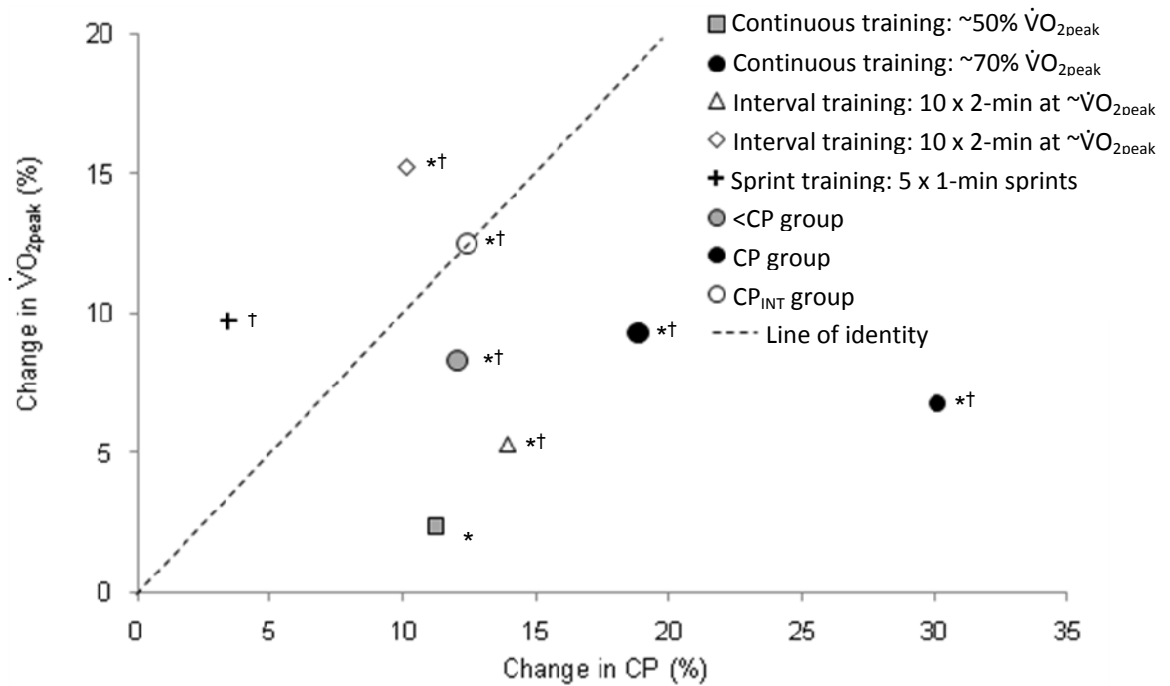
Figure 10.4: The effects of training on changes in Critical Power (CP) and $\dot{V}O_{2peak}$
Significant effect of training on: * CP (P < 0.05); † $\dot{V}O_{2max}$ (P < 0.05)

The training study data showed that total training duration required to achieve similar adaptations was significantly shorter when training at CP compared with training below CP and intermittently around CP. When considering exercise for health, this difference may have a significant impact on participant motivation and programme adherence, as a lack of time has been reported to consistently rank as an important perceived barrier to participation in physical activity (Ekkekakis, 2009). This concept is the basis for much of the research conducted by Gibala and colleagues, who have investigated the aerobic benefits of high-intensity interval training. Gibala and McGee (2008) propose that by developing original methods of prescribing exercise that will generate maximum benefits for a minimum outlay of time and effort, widespread activity levels and health may improve. The current study has shown that training at CP may be a practical method for achieving these time-effective fitness benefits.

**10.5) Future research directions**

*10.5.1) The causes of fatigue during exercise at Critical Power*

As with all forms of endurance exercise, identifying the causes of fatigue during exercise at CP for individuals is complex. Future work should focus on specific central and peripheral mechanisms that are likely to be related to the fatigue that is experienced during exercise around CP (i.e. prolonged, high-intensity aerobic exercise). These factors may incorporate physiological processes such as $K^+$, $Na^+$ and $Cl^-$ disturbances and reduced $K^+$-$Na^+$-ATPase activity (McKenna *et al.*, 2008), impaired sarcoplasmic reticulum $Ca^{2+}$ release (Allen *et al.*, 2008), reduced cerebral oxygenation (Secher *et al.*, 2008), increases in $H^+$, $P_i$ and muscle derived reactive oxygen species (Ferreira & Reid, 2008; Fitts, 2008) and respiratory muscle fatigue (Romer & Polkey, 2008). Furthermore, since TTE trials involve psychological factors such as motivation, concentration and a degree of pain tolerance, investigations into non-physiological factors associated with fatigue during exercise at and around CP would also be beneficial. Psychophysical effects of music, for example, have previously been shown to affect work output during constant-load exercise (Karageorghis & Terry, 1997), with music trials showing reductions in HR, blood pressure, $La^-$ and RPE (Szmedra & Bacharach, 1998). Furthermore, recent investigations into the role of the central nervous system in fatigue models have been extensive (Noakes *et al.*, 2005) and may contribute to the mechanisms associated with exercise at CP. This integrated approach to fatigue models is recognised by Hargreaves (2008) as a challenge for the future.

*10.5.2) Applications of Critical Power to sport and exercise sciences*

In chapter 1, sport and exercise sciences were identified as two separate strands of study, the former relating to the optimisation of athletic performance and the latter to ensuring health and well-being. While the current thesis has characterised CP across fitness groups and has applied CP in training within recreationally active individuals, future research may contribute to improving the application of CP by focusing on sport and exercise populations within their respective performance and exercise environments:

(i) *Athletic performance:* Controlled laboratory- and field-based studies would ascertain the effectiveness of CP as a marker of aerobic fitness within individual and team-sport athletes over a season or a period of consecutive seasons. Changes in CP measured in a laboratory setting relative to other measures of aerobic fitness (i.e., LT, $\dot{V}O_{2peak}$, economy or efficiency and/or $\dot{V}O_2$ kinetics) would help to estimate adaptations to training in the field using simple CP measures only. The use of CP-based training for improving competitive performance would be desirable for coaches, practitioners and athletes, but requires further investigation.

(ii) *Health and well-being:* The use of CP-based fitness monitoring and training interventions within healthy exercise settings (i.e., in public gyms) may be attractive due to the ease of measuring and monitoring CP in the absence of technical equipment and expertise. Controlled studies would ascertain whether CP-based training is able to meet public health objectives in terms of fitness outcomes, and whether it presents a motivating, achievable and practical training stimulus for non-athletes. With "more bang for you buck" in terms of time commitments, shorter-duration, higher-intensity sessions may prove more effective in maintaining exercise adherence.

## 10.6) Conclusion

The CP construct has received extensive research attention since it was scientifically introduced in the middle of the 20th century. Early studies described CP for isolated muscle groups and the construct was later applied to whole body exercise. Numerous methodological issues associated with the modelling and estimation of CP have been investigated, including the type of mathematical model used, the number and duration of trials required and the recovery duration between trials, etc. The CP estimate has been related to endurance performance for a variety of exercise modes and the physiological responses to exercise at CP have been examined.

Prior to completing this thesis the validity of CP across a range of fitness levels had not been examined, the reported physiological responses to exercise at CP were equivocal and CP-based training interventions remained to be trialled. Results have shown that CP, in relation to LT and $\dot{V}O_{2peak}$, is comparable between healthy males aged 19 – 44 y who differ in their aerobic fitness levels. In addition, while individual

responses are highly variable, this thesis supports exercise at CP as reflecting a non-steady state. The training study has shown that CP is sensitive to a variety of aerobic training interventions and, uniquely, has shown that CP may be used as a time-efficient and effective training intensity to improve aerobic fitness. By standardising methods of deriving CP estimates, as well as the methods used to report responses to exercise at CP over time, future work investigating the application of the CP construct may be more easily comparable.

# Glossary of Terms

| | |
|---|---|
| $\Delta$: | Difference between $\dot{V}O_2$ at lactate threshold and $\dot{V}O_{2max}$ (or $\dot{V}O_{2peak}$) |
| AT: | Anaerobic threshold |
| ATP: | Adenosine triphopshate |
| AWC: | Anaerobic work capacity |
| CI: | Confidence interval |
| $CO_2$: | Carbon dioxide |
| COPD: | Chronic obstructive pulmonary disease |
| CP: | Critical Power |
| CRS: | Critical running speed |
| CS: | Citrate synthase |
| CSS: | Critical swimming speed |
| CV: | Coefficient of variation |
| Hb: | Haemoglobin |
| $[HCO_3^-]$: | Extracellular bicarbonate concentration |
| H-PAQ: | Habitual physical activity questionnaire |
| HPAQ-SI: | Habitual physical activity questionnaire 'sport index' |
| $HR_{peak}$: | The highest heart rate measured during the incremental ramp test |
| IAT: | Individual anaerobic threshold |
| iEMG: | Integrated electromyogram |
| $La^-$: | Lactate |
| $La^-_{bl}$: | Blood lactate |
| $[La^-]_{bl}$: | Blood lactate concentration |
| LT: | Lactate threshold |
| MAP: | Maximal aerobic power |
| MLSS: | Maximal lactate steady state |
| MMP: | Maximal minute power attained during the incremental ramp test |
| $O_2$: | Oxygen |
| P: | Power output |
| $[PCr]$: | Phosphocreatine concentration |
| $pH_{bl}$: | Blood pH |
| $P_i$: | Inorganic phosphate |
| $[P_i]$: | Inorganic phosphate concentration |

| P-LT: | Power output at lactate threshold |
|---|---|
| $P_{max}$: | Instantaneous maximal power output |
| ^{31}P-MRS: | Phosphorous-31 magnetic resonance spectroscopy |
| P-$\dot{V}O_{2max}$: | Power output at $\dot{V}O_{2max}$ |
| $\dot{Q}_{max}$: | Maximal cardiac output |
| RAMP: | Incremental ramp test to exhaustion |
| RER: | Respiratory exchange ratio |
| RPE: | Rating of perceived exertion |
| SD: | Standard deviation |
| SDH: | Succinate dehydrogenase |
| SEE: | Standard error of the estimate |
| SEM: | Standard error of the mean |
| SPSS: | Statistical package for the social sciences |
| SRM: | Schoberer Rad Messtechnik |
| SSC: | Self-selected cadence |
| STPD: | Standardised temperature, pressure and dry gas |
| t: | Time |
| TTE: | Time to exhaustion |
| TWD: | Total work done |
| $\dot{V}CO_2$: | Volume of carbon dioxide produced per minute |
| $\dot{V}_E$: | Minute ventilation |
| v-LT: | Velocity associated with lactate threshold |
| v-MLSS: | Velocity associated with maximal lactate steady state |
| $\dot{V}O_2$: | Volume of oxygen consumed per minute |
| $\dot{V}O_2$-$CP_{est}$: | Estimated volume of oxygen consumed per minute at Critical Power |
| $\dot{V}O_2$-LT: | Volume of oxygen consumed per minute at lactate threshold |
| $\dot{V}O_{2max}$: | Maximal volume of oxygen consumed per minute |
| $\dot{V}O_{2peak}$: | The highest volume of oxygen consumed per minute during the RAMP |
| $\dot{V}O_2$-SC: | $\dot{V}O_2$ slow component |
| v-$\dot{V}O_{2max}$: | Velocity associated with $\dot{V}O_{2max}$ |
| w: | Work |
| W: | Watts |

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# Appendices

**Appendix A: Example participant information pack**

Chief Researcher:

**Kerry McGawley**
PhD Student

Phone: 01273 643754 (office)
      07941 009874 (mobile)
E-mail: K.Mcgawley@brighton.ac.uk

Supervisory Staff:

**Dr. Helen Carter**
E-mail: H.Carter@brighton.ac.uk

**Dr. Jeanne Dekerle**
E-mail: J.Dekerle@brighton.ac.uk

**Dr. Gary Brickley**
E-mail: G.Brickley@brighton.ac.uk

# Information Sheet

## An Investigation into the differing Activity and Fitness Levels on the Physiological Responses to Exercise at and around the Critical Power

### Purpose of the study

Critical power (CP) represents an exercise intensity that could, theoretically, be sustained for an infinite period of time. However, research shows that exercise at CP often causes exhaustion within one hour. The majority of CP research has used young (< 30 y), healthy, active, male participants. Despite CP providing a potentially useful tool for the exercise physiologist, its usefulness across a range of fitness groups has not been examined. The aim of the present study is to provide a detailed comparison of what happens to the body during exercise at and around CP for a range of population groups.

### Procedures

You will be required to complete:

- one incremental/ramp test,
- one time to exhaustion (TTE) familiarisation trial,
- three or four performance trials to determine CP
- three tests at and around CP (95%, 100% and 105% of CP).

All of the tests will be performed over 5 or 6 visits to the laboratory, with at least 24-h of rest between each visit (see table 1). *N.B., Visits do not have to be on alternate days over an 11-day period.* All tests will be performed on a cycle ergometer in our research laboratory.

Table 1: An example of the testing protocol

| Session | 1 | | 2 | | 3 | | 4 | | 5 | | 6 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Test 1 | Inc test | | TTE1 | | TTE3 | | CPa$_1$ | | CPb$_1$ | | CPc$_1$ |
| Recovery | 30 min | REST | 3 h | REST | 3 h | REST | | REST | | REST | |
| Test 2 | 1 x TTE$_f$ | | TTE2 | | TTE4 | | | | | | |

Key: Inc test = incremental/ramp test (for determination of lactate threshold and $\dot{V}O_{2max}$ ); TTE = time to exhaustion "critical power determination" trial; f = familiarisation; CP = trial at 95%, 100% or 105% of critical power; shaded cells represent minimum trials for completion

Visit 1

The **incremental/ramp test** will involve cycling against a light load that becomes increasingly heavier. Fingertip blood samples and expired air will be collected throughout this test and heart rate will be monitored. The **TTE familiarisation trial** will follow a 30-min recovery period, and involves cycling at a constant load until reaching exhaustion. This trial will last less than 15 min and will act as a practice trial to familiarise the participant with exhaustive exercise. No blood or air samples are collected.

Visits 2 and 3

Four **TTE trials** will be performed over the next two visits and involve cycling to exhaustion without any blood or air samples being taken.

Visits 4, 5 and 6

Participants will perform one or two constant-load exercise tests, **at and around CP**, on each of the final three visits. These tests will be performed at 95%, 100% and 105% of CP (in random order) and will be terminated at exhaustion. Blood samples and expired air will be collected at 5-min intervals and heart rate will be monitored throughout the test

Blood Samples:

During the incremental/ramp test and the tests at and around CP, fingertip blood samples will be taken for the measurement of selected metabolites and electrolytes. Samples will be drawn at rest, at specific time periods during the trials and post-exercise. Participants will experience a pin-prick sensation on the thumb prior to the sample, but the pain is minimal.

Heart Rate:

Heart rate will be monitored throughout the tests using a polar heart rate monitor.

**Benefits, Risks and Safety**

Benefits:
The benefits of this study include the opportunity for monitored exercise during each visit, the determination of common fitness measures (e.g., lactate threshold and $\dot{V}O_{2max}$) and personal CP data will be provided to individuals on request, following their final visit. This investigation will also provide useful information on how different populations respond to exercise at and around CP, outlining a potentially useful new tool for exercise tolerance and training.

Risks:
This study requires maximal effort testing and the experiments are demanding in nature. The risks include, but are not limited to, injuries of the muscles and tendons of the body. However, you will be thoroughly familiarised with the experimental procedures and equipment, and every effort will be made to minimise the risks by having all participants perform a thorough warm-up and cool-down during each testing session. The investigators are at all times vigilant in their continuous observation of you during exercise and the test will be terminated at your request, or if you appear to be unduly distressed. The blood samples will be taken by trained researchers with prior experience. There is a very minor risk of infection due to the blood sampling procedures, but this risk will be minimised by using sterilised equipment at all times. Your participation in this study does not prejudice any right to compensation, which you may have under statute or common law.

**Confidentiality of Data**

Personal details and test results will be treated confidentially at all times. Individual data will not be identifiable, but collective results may be published. Prior consent will be gained for any visual recordings (photographs) of any testing session and these recordings will remain under confidential storage and only published with your express permission. As a participant you are free to withdraw your consent to participate at any time. The researchers will answer any questions you may have in regard to the study at any time.

**Contact details**
If you have any queries throughout the testing process you can contact Kerry McGawley on Ph. 07941 009874 (24 h), or her supervisor Dr. Helen Carter on Ph. 01273 643743 (office hours).

# UNIVERSITY OF BRIGHTON
# CHELSEA SCHOOL
# WELKIN LABORATORIES

## PHYSIOLOGY MEDICAL QUESTIONNAIRE & INFORMED CONSENT

Name: …………………………………………………….. D.O.B.: ………………………

Address: …………………………………………………………………………………………….

………………………………………………… E-mail: ………………………………………….

Home tel.: …………………………………….. Mobile tel. no.:………………………………………

Emergency contact name: …………………………………. Tel. no.: ………………………………..

<u>MEDICAL HISTORY</u>

| | | |
|---|---|---|
| Are you in good health?<br>If NO, please explain: | Yes | No |
| Have you suffered from a serious illness or accident?<br>If YES, please explain: | Yes | No |

Do you suffer, or have you ever suffered from (please give particulars where appropriate):

| | | |
|---|---|---|
| Respiratory problems (e.g. asthma, bronchitis, COPD)? | Yes | No |
| High or low blood pressure? | Yes | No |
| Fainting, light-headedness or dizziness? | Yes | No |
| Heart problems (e.g. abnormal ECG, angina, atherosclerosis)? | Yes | No |
| Diabetes? | Yes | No |
| Epilepsy? | Yes | No |
| Any injuries or muscle, joint or bone problems? | Yes | No |
| Is there a history of any medical condition occurring in your immediate family?<br>If YES, please explain: | Yes | No |
| Do you feel pain in your chest when you do physical activity, or at other times?<br>If YES, please specify: | Yes | No |
| Have you had your cholesterol level measured?<br>If YES, what was the result (if known)? | Yes | No |

In the last 3 months, have you consulted your GP for any condition?    Yes   No
If YES, please give particulars:

Are you currently taking medication or dietary supplements?    Yes   No
If YES, please give particulars:

Do you have any other medical conditions or problems not previously mentioned?    Yes   No

Do you know of any other reason why you should not participate in physical activity?    Yes   No

## LIFESTYLE EVALUATION

Do you smoke?    Yes   No
If YES, how much?

On average, how many units of alcohol do you consume per week?
(1 unit = a pub measure of spirits, small glass of wine, half pint of lager) ………………… units

How would you describe your occupation (please tick)?

- Inactive (e.g. desk job)
- Light work (e.g. housework)
- Moderate work (e.g. gardening)
- Heavy work (e.g. lifting, carrying, digging)

Do you consider yourself to be physically INACTIVE?
(i.e., perform very little physical activity over the course of a week)    Yes   No

Do you walk or carry out physical activity on most days (at least four days per week)?    Yes   No
If YES, describe.

Do you participate in regular organised sport or exercise?    Yes   No
If YES, how often and what activities?

Do you train formally and participate in competition?    Yes   No
If YES, give details.

Would you describe yourself as physically well-trained?    Yes   No

Are you currently taking part (or recently taken part) in any other laboratory experiment?    Yes   No

Is there anything to your knowledge that may prevent you from
successfully completing the tests that have been outlined to you?    Yes   No

<u>DECLARATION</u>

I ………………………………………… (participant name) hereby volunteer to be a subject in experiments/investigations as of September 2006.


My replies to the above questions are correct to the best of my belief and I understand that they will be treated with the strictest confidence. The experimenter has provided me with full written information of, and I have understood the purposes of the experiment and possible risks involved.

I understand that I may withdraw from the experiment at any time and that I am under no obligation to give reasons for withdrawal or to attend again for experimentation.

I undertake to obey the laboratory/study regulations and the instructions of the experimenter regarding safety, subject only to my right to withdraw declared above.


Signature of Participant………………..…………………. Date:………………….

I ……………………………………………………. (the experimenter) have reviewed the above information given by the subject and consider that he/she is suitable to take part in this experiment/investigation.

Signature of Experimenter:………………..…………………. Date:………………….

**Appendix C: Habitual Physical Activity Questionnaire (H-PAQ)**

| | | | Experimenter Use |
|---|---|---|---|
| 1 | What is your main occupation? | …………………………………………….. | 1 − 3 − 5 |
| 2 | At work I sit… | never / seldom / sometimes / often / always | 1 − 2 − 3 − 4 − 5 |
| 3 | At work I stand… | never / seldom / sometimes / often / always | 1 − 2 − 3 − 4 − 5 |
| 4 | At work I walk… | never / seldom / sometimes / often / always | 1 − 2 − 3 − 4 − 5 |
| 5 | At work I lift heavy loads… | never / seldom / sometimes / often / always | 1 − 2 − 3 − 4 − 5 |
| 6 | After working I am tired… | very often / often / sometimes / seldom / never | 5 − 4 − 3 − 2 − 1 |
| 7 | At work I sweat… | very often / often / sometimes / seldom / never | 5 − 4 − 3 − 2 − 1 |
| 8 | Compared with others my age, my work is physically… | much heavier / heavier / as heavy / lighter / much lighter | 5 − 4 − 3 − 2 − 1 |
| 9 | Do you play sport? | yes / no | |
| | *If yes:* | | |
| | Which sport do you play most frequently? | …………………………………………….. | 0.76 − 1.26 − 1.76 |
| | How many hours a week? | <1 / 1-2 / 2-3 / 3-4 / >4 | 0.5 − 1.5 − 2.5 − 3.5 − 4.5 |
| | How many months a year? | <1 / 1-3 / 4-6 / 7-9 / >9 | 0.04−0.17−0.42−0.67−0.92 |
| | *If you play a second sport:* | | |
| | Which sport is it? | …………………………………………….. | 0.76 − 1.26 − 1.76 |
| | How many hours a week? | <1 / 1-2 / 2-3 / 3-4 / >4 | 0.5 − 1.5 − 2.5 − 3.5 − 4.5 |
| | How many months a year? | <1 / 1-3 / 4-6 / 7-9 / >9 | 0.04−0.17−0.42−0.67−0.92 |
| 10 | Compared with others my age, my physically activity is… | much more / more / the same / less / much less | 5 − 4 − 3 − 2 − 1 |
| 11 | During leisure time I sweat… | very often / often / sometimes / seldom / never | 5 − 4 − 3 − 2 − 1 |
| 12 | During leisure time I play sport… | never / seldom / sometimes / often / always | 1 − 2 − 3 − 4 − 5 |
| 13 | During leisure time I watch television… | never / seldom / sometimes / often / always | 1 − 2 − 3 − 4 − 5 |
| 14 | During leisure time I walk… | never / seldom / sometimes / often / always | 1 − 2 − 3 − 4 − 5 |
| 15 | During leisure time I cycle… | never / seldom / sometimes / often / always | 1 − 2 − 3 − 4 − 5 |
| 16 | How many minutes do you walk/cycle per day for transport? | <5 / 5-15 / 15-30 / 30-45 / >45 | 1 − 2 − 3 − 4 − 5 |

(Baecke *et al.*, 1982)

**Appendix D: Example calculation of respiratory gas exchange variables**

<u>Measurements</u>

| | | |
|---|---|---|
| a | Ambient pressure = | 759.06 mmHg |
| b | Expired air collection time = | 52.9 s |
| c | $FEO_2$ = | 18.21 % |
| d | $FECO_2$ = | 2.91 % |
| e | Expired air temperature = | 20.8 °C |
| f | Douglas bag volume = | 138.3 L |
| g | Sample volume = | 0.5 L |

<u>Calculations</u>

h  $\dot{V}E_{ATPS}$  = f + g = 138.3 + 0.5
= 138.80 L

i  $PH_2O$  = $(e^3 \times 0.00005) - (e^2 \times 0.0029) + (e \times 0.5449) + 3.4593$
= 13.99 mmHG

j  $\dot{V}E_{STPD}$  = h x [273/(273 + e)] x [(a - i)/760] x [60/b]
= 143.48 L·min$^{-1}$

k  $\dot{V}O_{2\ STPD}$  = [(20.93 x [j x (100 - [c + d])/79.04]) - (j x c)] / 100
= 3.84 L·min$^{-1}$

l  $\dot{V}CO_{2\ STPD}$  = j x [(d - 0.03)/100]
= 4.13 L·min$^{-1}$

m  $\dot{V}O_{2\ STPD}$  = (k x 1000)/body mass (77.40 kg)
= 49.64 mL·min$^{-1}$·kg$^{-1}$

n  $\dot{V}CO_{2\ STPD}$  = (m x 1000)/body mass (77.40 kg)
= 53.39 mL·min$^{-1}$·kg$^{-1}$

o  RER  = n/m
= 1. 1

**Appendix E: Individual $\dot{V}O_{2max}$ -criteria attainment during the RAMP**

| CRITERIA | | < 2.0 | ≥ 1.1 | > 90% | > 8.0 | ≥ 3 | |
|---|---|---|---|---|---|---|---|
| Group | Participant ID # | Δ $\dot{V}O_2$ (mL·kg$^{-1}$·min$^{-1}$) | RER | Predicted HR$_{max}$ | Peak [La$^-$]$_{bl}$ (mmol·L$^{-1}$) | Total criteria | Subset n = 8 |
| **Low** | 1 | 0.44 | 1.0 | 103% | 7.11 | 2 | |
| | 2 | 0.81 | 1.0 | 92% | 8.41 | 3 | ✓ |
| | 3 | 2.48 | 1.2 | 97% | 10.70 | 3 | ✓ |
| | 4 | 4.23 | 1.0 | 95% | 11.40 | 2 | |
| | 5 | 5.43 | 1.3 | 91% | 7.64 | 2 | |
| | 6 | 5.89 | 1.0 | 99% | 9.27 | 2 | |
| | 7 | 4.78 | 1.0 | 100% | 4.73 | 1 | |
| | 8 | 2.25 | 1.0 | 96% | 11.60 | 2 | |
| | 9 | 1.61 | 1.0 | 93% | 7.65 | 2 | |
| **Mod** | 10 | 2.58 | 1.0 | 93% | 7.80 | 1 | |
| | 11 | 5.77 | 1.0 | 92% | 6.86 | 1 | |
| | 12 | 0.17 | 1.0 | 104% | 10.30 | 3 | ✓ |
| | 13 | 1.60 | 1.0 | 105% | 8.06 | 3 | ✓ |
| | 14 | 4.04 | 1.0 | 96% | 9.66 | 2 | |
| | 15 | 4.65 | 1.0 | 97% | 7.79 | 1 | |
| | 16 | 1.18 | 1.0 | 106% | 6.21 | 2 | |
| | 17 | 3.95 | 1.1 | 101% | 10.80 | 3 | ✓ |
| **High** | 18 | 3.42 | 1.0 | 94% | 6.53 | 1 | |
| | 19 | 0.75 | 1.1 | 97% | 7.88 | 3 | ✓ |
| | 20 | 1.07 | 1.0 | 103% | 9.19 | 3 | ✓ |
| | 21 | 0.93 | 1.1 | 99% | 8.20 | 4 | ✓ |
| | 22 | 2.79 | 1.0 | 100% | 8.40 | 2 | |
| | 23 | 4.29 | 1.0 | 94% | 6.84 | 1 | |
| | 24 | 3.69 | 1.0 | 93% | - | 1 | |
| | 25 | 3.04 | 1.0 | 97% | 9.18 | 2 | |

**Appendix F: Example calculation of an adjusted mean coefficient of variation**

The following table shows the TTE data (in s) for the first two TTE trials (TTE1 and TTE2, respectively) for each of the participants in the SHORT and LONG groups. The CV (as a %) has been calculated for the pair of consecutive TTE trials (CV1-2). The final column shows the CV squared ($[CV1-2]^2$), with the 'adjusted' mean ($\sqrt{[\Sigma(CV^2)/n]}$) calculated at the bottom for each group of n = 4.

| Group | Participant ID # | TTE1 (s) | TTE2 (s) | CV1-2 (%) | $[CV1-2]^2$ |
|-------|--------------|----------|----------|-----------|-------------|
| SHORT | 1 | 113 | 123 | 6.0 | 35.9 |
| | 2 | 127 | 121 | 3.4 | 11.7 |
| | 3 | 130 | 129 | 0.5 | 0.3 |
| | 4 | 225 | 230 | 1.6 | 2.4 |
| | | | | $\sqrt{(\Sigma([CV1-2]^2)/n)}$ | 3.5 |
| LONG | 5 | 509 | 455 | 7.9 | 62.8 |
| | 6 | 586 | 377 | 30.7 | 942.0 |
| | 7 | 696 | 1058 | 29.2 | 851.9 |
| | 8 | 548 | 444 | 14.8 | 219.8 |
| | | | | $\sqrt{(\Sigma([CV1-2]^2)/n)}$ | 22.8 |

**Appendix G: Summary of correlations between LT, CP, $\dot{V}O_{2peak}$ and MMP variables**

| | P-LT (W) | P-LT (W·kg$^{-1}$) | P-LT (% of MMP) | $\dot{V}O_2$-LT (mL·kg$^{-1}$·min$^{-1}$) | $\dot{V}O_2$-LT (% of $\dot{V}O_{2peak}$) | $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$) | MMP (W) | MMP (W·kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| P-LT (W) | - | - | - | - | - | 0.77** | 0.83** | - |
| P-LT (% of MMP) | - | - | - | - | - | 0.45* | 0.33 | - |
| $\dot{V}O_2$-LT (mL·kg$^{-1}$·min$^{-1}$) | - | - | - | - | - | 0.93** | 0.71** | - |
| $\dot{V}O_2$-LT (% of $\dot{V}O_{2peak}$) | - | - | - | - | - | 0.45* | 0.30 | - |
| CP (W) | 0.81** | 0.68** | 0.33 | 0.71** | 0.27 | 0.81** | 0.97** | 0.83** |
| CP (W·kg$^{-1}$) | 0.79** | 0.86** | 0.90** | 0.85** | 0.42* | 0.67** | 0.80** | 0.98** |
| CP (% of MMP) | 0.55** | 0.53** | 0.24 | 0.53** | 0.12 | 0.65** | 0.65** | 0.68** |
| $\dot{V}O_2$-CP$_{est}$ (mL·kg$^{-1}$·min$^{-1}$) | 0.67** | 0.74** | 0.33 | 0.91** | 0.45* | 0.96** | 0.73** | 0.89** |
| $\dot{V}O_2$-CP$_{est}$ (% of $\dot{V}O_{2peak}$) | 0.16 | 0.27 | -0.08 | 0.49* | 0.25 | 0.51** | 0.31 | 0.49* |
| $\dot{V}O_2$-CP$_{est}$ (% of $\Delta$) | -0.13 | -0.06 | -0.45* | 0.16 | -0.24 | 0.31 | 0.19 | 0.25 |

* $P < 0.05$; ** $P < 0.001$

# Appendix H: Raw data from the pre-and post-training CP determination trials

| | Pre-training | | | | | | | | Post-training | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Power (W) | | | | Time (s) | | | | Power (W) | | | | Time (s) | | | |
| ID | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 1 | 271 | 219 | 240 | 206 | 230 | 611 | 418 | 783 | 303 | 276 | 228 | 245 | 177 | 214 | 860 | 442 |
| 2 | 312 | 249 | 245 | | 217 | 587 | 870 | | 335 | 267 | 246 | | 189 | 417 | 737 | |
| 3 | 316 | 270 | 235 | 237 | 239 | 353 | 854 | 900 | 316 | 267 | 285 | | 208 | 833 | 416 | |
| 4 | 273 | 235 | 225 | 240 | 273 | 602 | 909 | 553 | 302 | 273 | 235 | 258 | 177 | 228 | 734 | 461 |
| 5 | 261 | 228 | 218 | 200 | 253 | 421 | 467 | 800 | 300 | 262 | 233 | | 235 | 514 | 732 | |
| 6 | 206 | 166 | 159 | 150 | 174 | 340 | 422 | 897 | 242 | 206 | 186 | 195 | 177 | 444 | 1001 | 798 |
| 7 | 284 | 241 | 205 | 220 | 265 | 524 | 1500 | 909 | 329 | 284 | 248 | | 199 | 442 | 756 | |
| 8 | 247 | 226 | 205 | | 200 | 415 | 864 | | 300 | 247 | 236 | | 216 | 602 | 745 | |
| 9 | 163 | 130 | 122 | | 179 | 587 | 710 | | 170 | 163 | 145 | 135 | 181 | 368 | 501 | 797 |
| 10 | 279 | 220 | 195 | | 213 | 448 | 921 | | 329 | 279 | 253 | 266 | 192 | 359 | 901 | 484 |
| 11 | 223 | 190 | 203 | | 261 | 857 | 497 | | 264 | 223 | 215 | | 183 | 479 | 767 | |
| 12 | 187 | 148 | 146 | | 174 | 601 | 898 | | 229 | 201 | 187 | 168 | 127 | 264 | 437 | 727 |
| 13 | 278 | 219 | 205 | | 181 | 420 | 818 | | 309 | 278 | 244 | 220 | 146 | 297 | 503 | 901 |
| 14 | 202 | 134 | 125 | | 186 | 587 | 788 | | 240 | 202 | 153 | 166 | 79 | 168 | 888 | 428 |
| 15 | 288 | 230 | 209 | | 192 | 451 | 854 | | 314 | 288 | 256 | | 190 | 398 | 903 | |
| 16 | 171 | 150 | 155 | 161 | 230 | 920 | 903 | 467 | 219 | 171 | 196 | | 184 | 850 | 409 | |
| 17 | 262 | 228 | 205 | 217 | 287 | 507 | 989 | 719 | 273 | 260 | 224 | 217 | 288 | 364 | 524 | 876 |
| 18 | 263 | 209 | 200 | | 178 | 567 | 907 | | 263 | 230 | 229 | | 201 | 801 | 537 | |
| 19 | 326 | 272 | 255 | | 302 | 538 | 912 | | 363 | 272 | 291 | | 166 | 750 | 541 | |
| 20 | 248 | 210 | 193 | 178 | 307 | 435 | 538 | 721 | 248 | 190 | 193 | | 288 | 718 | 505 | |
| 21 | 196 | 149 | 141 | | 177 | 548 | 893 | | 218 | 179 | 170 | | 200 | 570 | 712 | |
| 22 | 191 | 150 | 159 | | 188 | 738 | 412 | | 229 | 200 | 165 | 150 | 122 | 172 | 465 | 748 |
| 23 | 379 | 345 | 339 | 324 | 305 | 547 | 602 | 884 | 401 | 379 | 333 | | 284 | 414 | 825 | |
| 24 | 280 | 232 | 221 | 229 | 212 | 580 | 986 | 839 | 314 | 280 | 237 | 260 | 285 | 546 | 911 | 704 |
| 25 | 334 | 289 | 261 | | 204 | 422 | 763 | | 384 | 323 | 300 | 289 | 174 | 365 | 490 | 795 |
| 26 | 326 | 283 | 271 | 261 | 232 | 508 | 517 | 832 | 375 | 326 | 298 | | 213 | 454 | 711 | |
| 27 | 268 | 200 | 209 | 205 | 182 | 716 | 432 | 560 | 285 | 268 | 230 | | 171 | 250 | 731 | |
| 28 | 334 | 283 | 255 | | 219 | 372 | 767 | | 334 | 334 | 266 | 289 | 240 | 240 | 858 | 405 |
| 29 | 268 | 230 | 215 | | 271 | 564 | 717 | | 324 | 257 | 254 | | 197 | 731 | 583 | |
| 30 | 155 | 135 | 129 | 125 | 175 | 500 | 502 | 856 | 186 | 155 | 148 | | 182 | 369 | 737 | |
| 31 | 260 | 215 | 236 | 207 | 202 | 599 | 292 | 713 | 298 | 260 | 239 | | 182 | 394 | 869 | |
| 32 | 357 | 303 | 279 | | 193 | 431 | 796 | | 382 | 323 | 303 | | 216 | 603 | 790 | |
| 33 | 205 | 158 | 150 | | 179 | 480 | 887 | | 224 | 205 | 180 | 164 | 204 | 257 | 428 | 752 |
| 34 | 178 | 140 | 133 | | 186 | 579 | 719 | | 209 | 186 | 158 | 140 | 113 | 221 | 486 | 779 |
| 35 | 259 | 219 | 209 | 204 | 227 | 572 | 583 | 800 | 290 | 245 | 259 | | 186 | 742 | 550 | |
| 36 | 301 | 265 | 218 | 237 | 215 | 341 | 908 | 667 | 311 | 301 | 264 | 245 | 238 | 321 | 520 | 775 |
| 37 | 212 | 159 | 172 | | 181 | 818 | 602 | | 229 | 212 | 185 | 175 | 178 | 254 | 420 | 724 |
| 38 | 260 | 210 | 202 | | 178 | 422 | 725 | | 302 | 260 | 240 | 220 | 181 | 309 | 490 | 884 |
| 39 | 274 | 226 | 201 | | 245 | 509 | 799 | | 310 | 274 | 265 | 250 | 147 | 293 | 500 | 845 |
| 40 | 237 | 180 | 199 | | 200 | 909 | 437 | | 261 | 237 | 216 | 206 | 187 | 285 | 514 | 845 |
| 41 | 353 | 306 | 274 | | 241 | 414 | 831 | | 380 | 353 | 312 | 279 | 228 | 286 | 453 | 907 |
| 42 | 298 | 246 | 269 | 258 | 251 | 873 | 396 | 528 | 325 | 303 | 258 | 253 | 171 | 252 | 564 | 763 |
| 43 | 264 | 230 | 210 | | 199 | 478 | 850 | | 317 | 264 | 272 | | 208 | 775 | 460 | |