

The response of the 'Critical Power' concept to both acute and chronic interventions as determined by the 3-min all-out cycling test.

Submitted by **Leonard Samuel Parker Simpson** to the University of Exeter as a thesis for the degree of Doctor of Philosophy in Sport and Health Sciences in September 2014.

This thesis is available for library use on the understanding that it is copyright material and that no quotation from this thesis may be published without proper acknowledgement.

I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University

Signature:

Acknowledgements

As with any PhD, this has not been a smooth ride. However, a 'smooth ride' is something we look to retire into; something we look for when we can't take the jolts and the bumps from the fast ride we're on. I'm grateful for the jolts and the bumps (with hindsight) and thank my supervisory team for providing me with personal and professional challenges. I have learnt much both in and out of the lab. It has been a privilege to become Dr Wilkerson's inaugural PhD student; something he must have regretted and doubted too many times to remember. He has stood strong by me when it would have been easy to leave and has allowed me the freedom to make my own mistakes.

I must thank the wider research team at Exeter; Professor Jones, Anni, Fred, Stevo and Phil. Anni and Andy, thanks for all your input over the past 6 years – it hasn't gone unnoticed. Phil, some of the discussions I had with you are amongst my most memorable; I for one thoroughly enjoy your 'wild speculation', probably because you sell it as founded in some form of evidence! Stevo, you probably won't know this, but you were (and still are) the 'Criterion' PhD student. The 'gold standard' which became the unassailable expectation of the group; this is a good thing, so thank you. I'm just glad that (for now) we want different careers; otherwise, I'd be out of a job.

Which brings me to thank the English Institute of Sport. Dr Jamie Pringle; thank you for igniting (or certainly blowing on) the flames back in 2008 where I first stated 'playing' with the all-out test. Without this enthusiasm and encouragement, I may very well have not ended up where I am now. Additionally, Dr Jonathan Leeder, Dr Paul Barratt and Andy Harrison - thanks for being so supportive of me finally getting this document written. Without that support, I wouldn't have been able to hit the deadline.

Thanks need to go to Prof. Craig Williams and Dr Mark Burnley, not only for taking the time to read this document but then offer a further 3+ hours to discuss this work with me in the Viva. Craig it was nice to almost come full circle having initially learned from you as my undergraduate supervisor all those years ago, it was good to have you examine me once more. Mark, it was a genuine

honour to discuss and defend this work in front of the all-out test founder; thanks for agreeing to cast your knowing eye and critical mind over my work.

Finally, but most importantly of all, I must thank my family. This has been a total of 6 years of “I can’t make it” and “maybe next times” due to metaphorically carrying this document on my shoulders. Thank you for your unflappable support and understanding. To my partner Suz, while it didn’t feel unfortunate at the time, getting together in year 1 of this “3-year PhD”, it has become somewhat of a burden for you as well. Thank you for sticking it out with me and I look forward to the future and the additional head-space to think about “us” more often. You have pulled me through this and made this possible – thank you again.

It would be remiss of me to not acknowledge each and every “willing” participant who took part in this work contained within. The 3-min all-out test is genuinely one of the most horrific experiences you can give to yourself. I can still (some 3 years after my last attempt) mentally put myself back on the bike with 90 seconds to go before test onset and experience the cold sweat and the utter desire to just not do it. And in every study contained within this thesis, the minimum sentence was four 3-min tests, with many completing up to 8 within a short space of time. So thanks for coming back after the first one!

As a closing remark, I’m incredibly fortunate and enthused to be taking the knowledge and understanding gained as part of this PhD journey and using almost all of it daily. I don’t meet many people with PhDs who are able to directly use their doctoral research to inform their daily practice. I am able to obtain power-duration relationships from professional cyclists to help understand how their training is affecting their physiology and what sort of performances we can expect from them. None of this would be possible if I hadn’t been given this opportunity, so thanks Daryl, I owe you one (or twelve)!

Abstract

The hyperbolic relationship between power output and endurance time can be measured using all-out exercise. The aims of this thesis were to (i) assess whether the all-out test could be used under novel testing protocols to provide valid power-duration (P-D) parameter estimates; and (ii) attempt to elucidate the likely physiological composition of the P-D curvature constant.

All-out tests were initiated from moderate-(M), heavy-(H) and severe-(S2 & S4) intensity 'baselines' (chapter 4). The work performed above end power (WEP) was not different to control under M or H conditions but was significantly, predictably reduced under the S2 & S4 conditions (control: 16.3 ± 2.2 ; M: 17.2 ± 2.4 ; H: 15.6 ± 2.3 kJ, $P > 0.05$; S2: 11.5 ± 2.5 ; S4: 8.9 ± 2.2 kJ, $P < 0.05$). The 3-min all-out test end power (EP) parameter was unaffected.

Muscle glycogen may form part of the WEP. Type I (T1) and type II (T2) muscle fibres were depleted of their glycogen content prior to the all-out test (chapter 5). EP and WEP were unaffected by either T1 or T2 glycogen depletion.

The all-out tests was conducted under hypoxic conditions alongside the criterion assessment of the P-D relationship (chapter 6). Normobaric moderate hypoxia caused a reduction in CP (control: 175 ± 25 ; hypoxia: 132 ± 17 W, $P < 0.001$) without affecting W' (control: 13.2 ± 2.2 ; hypoxia: 12.3 ± 2.7 kJ, $P > 0.05$). The 3-min all-out test provided EP and WEP estimates, which did not differ to CP and W' (control: EP 172 ± 30 W, WEP 12.0 ± 2.6 kJ; hypoxia EP 134 ± 23 W, WEP 12.5 ± 1.4 kJ, $P > 0.05$) providing the ergometer resistance was adjusted for the hypoxic conditions. Furthermore, a significant negative relationship was observed between $\% \Delta (\dot{V}O_{2peak} - CP)$ and $\% \Delta W'$ ($r = -0.83$, $P < 0.001$); thus, W' may represent the relative 'size' of the severe-intensity domain.

The all-out test was used to track training-induced changes in P-D parameters in response to 6-weeks of sprint or endurance training (chapter 7). EP & WEP were differently altered compared to CP and W' following sprint training (CP 12 ± 9 ; EP -0 ± 9 % change; W' -5 ± 25 ; WEP 11 ± 15 % change). The all-out test reliably tracked changes in CP and W' following endurance training.

In conclusion, the all-out test provides reliable EP and WEP values. Its validity is acceptable, but is perhaps affected by exercise training that is specific to the execution of the test. The W' appears to be determined, to a large extent, by the relative size of the severe-intensity domain.

Contents

Section:	Page:
Acknowledgements	2
Abstract	4
List of Tables	10
List of Figures	11
List of Abbreviations	12
Publications	13
Communications	13
CHAPTER 1 - INTRODUCTION	14
1.1. The Critical Power Concept	15
1.2. Maximal Oxygen Uptake	16
1.3. Lactate Threshold	18
1.4. Maximum Lactate Steady State	20
1.5. Central (nervous system) Fatigue	22
1.6. Exercise Intensity Domains	23
1.6.1. Moderate-intensity	23
1.6.2. Heavy-intensity	24
1.6.3. Severe-intensity	25
1.6.4. Extreme-intensity	25
1.7. Normalising Exercise intensity	26
1.8 Validity and Reliability	28
1.8.1. Validity	28
1.8.2. Reliability	29
1.8.3. Resilience	29
1.8.4. Sensitivity	29
1.8.5. Precision	29
1.8.6. Accuracy	29
1.9. Direction	30
CHAPTER 2 - LITERATURE REVIEW	31
2.1. The Critical Power Parameter	31
2.2. Conventional Methods of Determining the CP and W'	32
2.2.1. 2-parameter CP model	32

2.2.2. 2-Parameter critical power model assumptions	34
2.2.3. 3-parameter CP model	37
2.2.4. Exponential model	38
2.2.5. Influence of mathematical model on CP & W'	38
2.2.6. Alternative exponential model	40
2.2.7. Duration of predicting trials	41
2.3. All-Out Method of Determining CP and W'	43
2.4. Tolerance to Exercise 'at' CP	50
2.5. Predicting Exercise Tolerance	52
2.6. The Curvature Constant (W') of the P-D Relationship	54
2.6.1. Putative underpinnings of the W' parameter	59
2.6.2. Summary	64
2.7. Skeletal Muscle Fatigue	65
2.7.1 Muscle action	65
2.7.2. Extracellular K ⁺	66
2.7.3 Inorganic Phosphate (P _i)	67
2.7.2. pH/H ⁺	68
2.8. Influencing the Magnitude of P-D Parameters with Training	69
2.9. Adaptations to Exercise Training; Enhancing 'Aerobic' Capabilities	76
2.10. Anaerobic Adaptations to Exercise Training	78
2.10.1. Muscle fibre type	78
2.10.2. Muscle glycogen	79
2.10.3. Glycolytic enzymes	80
2.10.4. Muscle buffering	81
2.11. Effect of Inspired Oxygen Fraction on the CP and W'	83
2.12. Aims and Hypotheses	86
2.12.1. Research questions & hypotheses	88
CHAPTER 3 - GENERAL METHODS	90
3.1. Health and Safety	90
3.2. Participants	91
3.3. Cycle Ergometers	91
3.4. Ramp-Incremental Test	92
3.5. Normalising Exercise Intensities	93
3.6. 3-min All-Out Test	94
3.7. Measurement of Pulmonary Gas Exchange	97

3.8. Measurement of Blood Lactate Concentration	98
CHAPTER 4 – INFLUENCE OF INITIAL METABOLIC RATE ON THE POWER-DURATION RELATIONSHIP FOR ALL-OUT EXERCISE	101
4.1. Introduction	101
4.2. Methods	102
4.2.1. Subjects	102
4.2.2. Experimental design	103
4.2.3. Determination of $\dot{V}O_{2peak}$ and GET	104
4.2.4. 3-min all-out cycling tests	104
4.2.5. Statistical analysis	105
4.3. Results	106
4.5. Discussion	109
Perspective 1	113
CHAPTER 5 – EFFECT OF TYPE I AND TYPE II MUSCLE FIBRE-SPECIFIC GLYCOGEN DEPLETION ON ‘CRITICAL POWER’ AND <i>W'</i> DETERMINED USING THE 3-MIN ALL-OUT CYCLING TEST	114
5.1. Introduction	114
5.2. Methods	116
5.2.1. Determination of $\dot{V}O_{2peak}$ and GET	116
5.2.2. Estimation of critical power and <i>W'</i>	116
5.2.3. Glycogen depletion protocols	117
5.2.4. Pulmonary gas analysis	118
5.2.5. Blood lactate & blood glucose analysis	118
5.2.6. Dietary manipulation	118
5.2.7. Statistical analysis	119
5.3. Results	119
5.4. Discussion	123
Perspective 2	130
CHAPTER 6 – INFLUENCE OF HYPOXIA ON THE POWER-DURATION RELATIONSHIP DURING HIGH-INTENSITY EXERCISE	131
6.1. Introduction	131
6.2. Methods	132
6.2.1. Subjects	132
6.2.2. Experimental design	132
6.2.3. Equipment	133
6.2.4. Incremental test	134
6.2.5. Power-duration relationship	134
6.2.6. All-out cycling test	134

6.2.7. Statistical analysis	135
6.3. Results	135
6.3.1. CP and W' estimates from the conventional protocol	136
6.3.2. CP and W' estimates derived from the all-out test	139
6.3.3. Comparisons between conventional and all-out test CP and W' estimates	140
Discussion	142
Perspective 3	147
CHAPTER 7 – EFFECT OF 6-WEEKS OF SPRINT-INTERVAL OR ENDURANCE TRAINING ON THE POWER-DURATION RELATIONSHIP FOR SEVERE-INTENSITY EXERCISE IN HUMANS	148
7.1. Introduction	148
7.2. Methods	151
7.2.1. Participants	151
7.2.2. Pre-training assessments	151
7.2.3. CP and W'	151
7.2.4. EP and WEP	152
7.2.5. Pairing	152
7.2.6. Training protocol	152
7.2.7. Statistical analysis	153
7.3. Results	155
7.3.1. Comparison of SIT and END training	155
7.3.2. Comparisons of conventional and all-out estimations	160
7.4. Discussion	163
7.4.1. Training-induced alterations in the conventionally derived P-D relationship	163
7.4.1. 3-min all-out test parameters	167
Perspective 4	171
CHAPTER 8 – GENERAL DISCUSSION	172
8.1. Summary of the Main Findings	172
Chapter 4; elevated baseline	172
Chapter 5; glycogen depletion	173
Chapter 6; hypoxia	173
Chapter 7; training	174
8.2. Reliability and Validity of the All-Out Test	174
8.2.1. End power (EP)	175
8.2.2. Work above end power (WEP)	177
8.2.3. Predicting severe-intensity exercise tolerance:	179
8.2.4. Summary	181
8.3. Response of EP to Specific Manipulation	182

8.4. WEP Responses to Specific Manipulation	183
8.5. Limitations	189
8.5.1. Experimental limitations	189
8.6. Contribution to the Area	192
8.7. Practical Applications	193
8.8. Future Directions	193
8.8. Conclusion	195
Bibliography	198

List of Tables

Table Number & Title	Page
Table 2.1. Difference in CP & W' estimates from five mathematical models.....	40
Table 2.2. Reliability of CP/EP and W'/WEP summary.	49
Table 2.3. Training-induced changes in $\dot{V}O_{2max}$, CP and W'.	75
Table 2.4. Training-induced changes in exercise performance.	77
Table 4.1. Mean (\pm SD) 3-min all-out parameters from trial conditions.	106
Table 5.1. Mean (\pm SD) 3-min test parameters under each condition.	120
Table 6.1. Mean (\pm SD) data from conventional exhaustive exercise trails.....	136
Table 6.2. Mean (\pm SD) 3-min all-out test variables from each condition.	137
Table 7.1. Pre- and post-training group mean values (\pm SD).	157
Table 7.2. Comparison of SIT Vs. END for altering measured parameters.....	158
Table 7.3. Conventional and all-out parameter data, pre- and post-training. ..	161

List of Figures

Figure number & title	Page
Figure 3.1. GET Determination.....	93
Figure 3.2. Linear relationship between torque & cadence in linear mode.....	95
Figure 3.3. Exponential relationship between power & cadence in linear mode.	96
Figure 3.4. Correctly and incorrectly performed 3-min all-out tests.....	99
Figure 4.1. Schematic of experimental protocol.	103
Figure 4.2. Mean 3-min all-out test power profile.	108
Figure 4.3. Mean $\dot{V}O_2$ response under each condition.....	109
Figure 5.1. Post 3-min test [Bla] response.	120
Figure 5.2. Type I depletion protocol mean $\dot{V}O_2$ response.....	121
Figure 5.3. Mean 3-min test power profiles.	122
Figure 5.4. Mean 3-min test $\dot{V}O_2$ profiles.....	123
Figure 6.1. Relationship between change in W' and change in CP.....	138
Figure 6.2. Relationship between change in W' and the change in $\dot{V}O_{2peak} - CP$	139
Figure 6.3. Mean 3-min power profiles from each test condition.....	140
Figure 6.4. Validity and agreement between all-out and conventional CP.	141
Figure 6.5. Validity and agreement between all-out and conventional W'	142
Figure 7.1. Schematic of experimental design.	153
Figure 7.2. SIT and END training volume and intensity comparison.	155
Figure 7.3. SIT group mean training performances over training period.	156
Figure 7.4. Conventional P-D and work vs. time relationships pre- and post- training.	159
Figure 7.5. Mean 3-min power and $\dot{V}O_2$ responses pre- and post-training.	160
Figure 7.6. Linear regression of all-out vs. conventional parameters.....	162
Figure 8.1. Validity and agreement of all-out and conventional CP.....	176
Figure 8.2. Validity and agreement of the all-out and conventional W'	178
Figure 8.3. T_{lim} predictive capacity of all-out and conventional P-D parameters.	181

List of Abbreviations

[Bla]	Blood lactate concentration
[K⁺]_{ex}	Interstitial/extracellular potassium concentration
[Mg²⁺]_i	Myoplasmic/intracellular free magnesium concentration
CP	Critical Power
CV	Coefficient of variation (standard deviation/mean)
Δ	Delta (change or difference)
EP	End power of the 3-min all-out test
F_iO₂	Fraction of inspired oxygen
GE	Gross efficiency
GET	Gas exchange threshold
HR	Heart rate
kJ	Kilojoule
LT	lactate threshold
LF	Linear factor (resistance setting of Lode cycle ergometer)
P-D	Power-duration
PCr	Phosphocreatine
P_i	Inorganic Phosphate
PPO	Peak (mechanical) power output
P_{ramp}	Peak (adjusted) ramp-incremental power output
rpm	Revolutions per minute (cadence)
SEE	Standard error of the estimate
S_pO₂	Arterial oxygen saturation
SR	Sarcoplasmic reticulum
TE	Typical error
T_{lim}	Time to exhaustion
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximum oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen uptake
W	Watt
W'	Curvature constant of the power-duration relationship
WEP	Work performed above EP during the 3-min all-out test

Publications

Parker Simpson, L., Jones, A. M., Vanhatalo, A., Wilkerson, D. P. (2012). Influence of initial metabolic rate on the power-duration relationship for all-out exercise. *European Journal of Applied Physiology*, **112**, 2467-73.

Parker Simpson, L., Jones, A. M., Skiba, P. F., Vanhatalo, A., Wilkerson, D. P. (2014). Influence of hypoxia on the power-duration relationship during high-intensity exercise. *International Journal of Sports Medicine*, (In Press).

Communications

Parker Simpson, L., Jones, A. M., Vanhatalo, A., Wilkerson, D. P. (2010). Influence of initial metabolic rate on the parameters of the 3-min all-out cycling test in men. *Medicine and Science in Sport and Exercise*, **42 (5)**, 30. (Abstract).

Parker Simpson, L., Jones, A. M., Vanhatalo, A., Wilkerson, D. P. (2011). Influence of fibre-specific muscle glycogen depletion on the parameters of the 3-min all-out cycling test. *Medicine and Science in Sport and Exercise*, **43 (5)**, 775. (Abstract).

Parker Simpson, L., Jones, A. M., Vanhatalo, A., Wilkerson, D. P. (2013). Hypoxia reduces the critical power but not the curvature constant of the power-duration relationship. *Medicine and Science in Sport and Exercise*, **45 (5)**, 630-634. (Abstract).

Chapter 1 - Introduction

Any athlete would be able to testify to the reduction in their average running speed or power output as they compete over increasing distances or durations. Indeed, if Usain Bolt could complete a 10 km race at his world record 100 metre race speed, he would finish the 10 km distance in around 15 min 58 s. This would be some 40 % faster than the current 10 km world record, which stands at 26 min 17.53 s. Yet, if Stephan Nimke's sea level kilometre time trial world record (1:00.082 (min:ss.000); 59.92 kph) were extrapolated out to the 4km individual pursuit, the event would be completed in around 4:00.04 just 4 % faster than the 4km world record of 4:10.534. When average speeds for world records within the same sport are plotted against event distance, a consistent relationship emerges – a hyperbolic curve (Lloyd, 1966).

The cycling kilometre time trial is a maximal event requiring the completion of 1000 m as quickly as possible. Interestingly, if the power profile of Stephan Nimke's kilometre world record were to be inspected, the following would be observed; following the initial increase in power output up to a 'peak' value, his power will have fallen progressively over the remaining ~ 50 s in a remarkably similar 'curve' to that of the speed-distance relationship of world records. It would appear that, while on a more macro-level, human performances conform to a hyperbola, even on a micro, effort-by-effort basis, human performance may conform to a hyperbola, providing the effort is maximal or 'all-out'.

This consistent observation in human and muscle performance capability is intriguing and has (over the past decade) led to the use of all-out exercise as a means to measure or quantify performance capabilities over durations from around 2 to 45 min. The characteristics of an individual 'curve' can be used to predict performance capability for a given distance/duration with far better accuracy than other, more typical or classical laboratory-derived parameters used to 'understand' human performance. A single, short-duration, all-out exercise bout becomes an attractive and arguably more ecologically valid measure of performance capabilities. Furthermore, it has the potential to expedite our understanding of the underlying physiology, which dictate the characteristics of the curve; that being the steepness and the magnitude of the

'levelling off' of the curve. A mechanistic understanding of these curves characteristics arms scientists and/or athletes/coaches with information that can be used to understand/enhance performance for a given discipline.

1.1. The Critical Power Concept

The critical power (CP) concept was initially formulated in mid 1950 in France by Hugues Monod and Jean Scherrer when they described the work that can be performed by a muscle either dynamically or isometrically across a range of durations (Monod & Scherrer, 1957). This seminal piece of work was later translated into English and published in *Ergonomics* in the mid 1960s (Monod & Scherrer, 1965). Some 15 years later Moritani (1981) expanded the model to whole body exercise. The CP model describes the hyperbolic relationship between exercise intensity and endurance time. In its simplest description, very high exercise intensities can be maintained for a matter of seconds with performance being limited by predominantly mechanical constraints (Martin, Brown, Anderson, & Spirduso, 2000). However, much lower intensities of exercise may be continued for 'long' durations with the limitations to exercise becoming predominantly metabolic (Amann, 2011; Bundle, Ernst, Bellizzi, Wright, & Weyand, 2006; Bundle & Weyand, 2012). The CP represents the power asymptote of the hyperbolic intensity-time relationship. The curvature constant of the hyperbola, notionally termed the W' , represents a fixed magnitude of work that may be performed above the CP with exhaustion occurring upon completion of this fixed amount of work (Fukuba et al., 2003; Jones, Vanhatalo, Burnley, Morton, & Poole, 2010). The CP theoretically represents the exercise intensity below which exercise may continue indefinitely without fatigue. Above the CP exercise may continue until the work equivalent to the magnitude of the W' has been completed, at which point exercise must stop, or the intensity reduce to, or below, the CP (Burnley, Doust, & Vanhatalo, 2006a; Jones et al., 2010). While the CP and the W' must be underpinned by physiological processes, the parameters themselves are a 'high-level' glimpse into muscular capabilities spanning ~ 2 to 45 min (Burnley & Jones, 2007).

Conventionally the CP and W' have been determined through the completion of a series of (3 to 7) constant-power exercise trials continued to volitional exhaustion spanning duration of 1 to 15 minutes (Hill, 1993; Poole, Ward, Gardner, & Whipp, 1988). Although the relationship could be derived from just two exhaustive exercise trials, the mathematical 'fit' of the model would be considered 'perfect'. Whereas, three or more trials used to estimate the CP and W' parameters provides details about the reliability of the parameter estimates through the standard error of the estimate (SEE) and the R^2 of the model used in their derivation. However, more recently the CP and W' parameters have been postulated, and then experimentally shown, to be predictable from all-out exercise testing (Vanhatalo, Doust, & Burnley, 2007). Using the same fundamental premise of the CP concept but applying it to all-out exercise results in the following: when a maximal effort is initiated and sustained for a prolonged period (~ 3 min), the W' or finite amount of supra-CP work, is completed initially. Once W' is 'expended' fully, the highest exercise intensity that should be attainable is that of the CP. This elegantly simple approach to measuring CP and W' offers an attractive alternative to the conventional method, due to its potential to expedite our understanding of the physiological underpinnings of both the CP and W' . These two parameters, while being distinct from other, more 'typical' physiological parameters, correlate with and may be (to some extent at least) determined by the more 'typical' physiological landmarks such as maximal oxygen uptake, lactate threshold and maximal lactate steady state.

1.2. Maximal Oxygen Uptake

A plateau in the rate of oxygen uptake ($\dot{V}O_2$) in the face of a continually increasing power output is known as the maximal oxygen uptake ($\dot{V}O_{2max}$; (Bassett & Howley, 2000; Levine, 2008; Wagner, 1996)). Ever since the turn of the 20th century exercise physiologists have been fascinated with the maximal rate at which atmospheric oxygen (O_2) can be transported to the mitochondria and utilised to support oxidative ATP resynthesis (Hill & Lupton, 1923; Levine, 2008). The $\dot{V}O_{2max}$ was originally believed to represent the maximal ability of the heart and circulatory system to deliver O_2 to the working muscles and for the muscles to extract and utilise this O_2 within the mitochondria (Bassett & Howley,

1997). Since, differing viewpoints have emerged suggesting that the brain and central motor drive play a role in preventing the 'true' attainment of the maximal capabilities of the cardiovascular, metabolic and neural systems as, in doing so would cause catastrophic disturbance to homeostasis (Noakes, Peltonen, & Rusko, 2001; Noakes & St Clair Gibson, 2004; Noakes, St Clair Gibson, & Lambert, 2004). However, while the brain is certainly required for muscle action, and high levels of motivation for the attainment of $\dot{V}O_{2max}$, at sea level, when no further increase in $\dot{V}O_2$ is measured despite a continued increase in external muscular force output, this must represent the $\dot{V}O_{2max}$ (Bassett & Howley, 2000; Levine, 2008). The $\dot{V}O_{2max}$ is one of the most widely measured physiological parameters in exercise physiology and is often used as an indicator of 'fitness' or training status (Bassett & Howley, 2000). However, a plateau in $\dot{V}O_2$ is not always observed during incremental exercise, with exhaustion occurring prior to the attainment of the $\dot{V}O_{2max}$ (Day, Rossiter, Coats, Skasick, & Whipp, 2003). In these circumstances the term $\dot{V}O_{2peak}$ is adopted, representing the highest $\dot{V}O_2$ measured during incremental or sustained high-intensity exercise continued until volitional exhaustion. Although the term $\dot{V}O_{2peak}$ is adopted in the absence of a $\dot{V}O_2$ plateau, it is likely that the $\dot{V}O_{2peak}$ and $\dot{V}O_{2max}$ are functionally the same value in healthy participants providing a maximal voluntary effort (Day et al., 2003).

The likely physiological underpinnings of the $\dot{V}O_{2max}$ include; (i) the maximal cardiac output; (ii) the oxygen carrying capability of the blood; (iii) pulmonary diffusing capacity and; (iv) the composition of the exercising musculature (Bassett & Howley, 2000). A muscle with a large number of mitochondria, oxidative enzymes and a high capillary:muscle fibre ratio has the potential to create a favourable O_2 diffusion gradient which may also contribute to the magnitude of the $\dot{V}O_{2max}$ (Bassett & Howley, 2000; Wagner, 1992). However, while $\dot{V}O_{2max}$ is often used to characterise elite and non-elite athletes, it is perhaps the ability to utilise a high percentage of the $\dot{V}O_{2max}$ for sustained periods that has a greater bearing on exercise performance (Costill, Thomason, & Roberts, 1973; Coyle, 1999; Maughan & Leiper, 1983). Furthermore the efficiency with which the body generates external power is likely to play a considerable role in exercise performance, particularly over longer-duration performances (Coyle, 1999). Typical gross efficiency (the ratio between energy

expended and energy consumed, expressed as a percentage; (Moseley & Jeukendrup, 2001)) during cycling is between 18 – 26 % (Coyle, Sidossis, Horowitz, & Beltz, 1992; Hopker, Jobson, Carter, & Passfield, 2010; Lucia, Hoyos, Perez, Santalla, & Chicharro, 2002) and in competitive cyclists an inverse relationship ($r = -0.72$) between gross efficiency (GE) and $\dot{V}O_{2max}$ can be observed (Lucia et al., 2002). So while the $\dot{V}O_{2max}$ is undoubtedly a key factor in determining exercise performance capability or exercise tolerance, it is not the only factor. Certainly as exercise intensity becomes progressively more submaximal (intensity falls further below that associated with the $\dot{V}O_{2max}$), other physiological parameters become more associated with exercise performance (Burnley & Jones, 2007; Jones & Carter, 2000).

1.3. Lactate Threshold

The lactate threshold (LT) represents the first increase in blood lactate concentration ([Bla]) above resting levels as exercise intensity increases (Jones & Carter, 2000). The LT typically occurs somewhere between ~ 50 to 75 % $\dot{V}O_{2max}$ (Gaesser & Poole, 1986; Spurway, 1992) and usually (although not always) coincides with the gas exchange threshold (GET; (Jones & Carter, 2000; Spurway, 1992)). The GET is described by the point at which there are non-linear increases in minute ventilation (V_E) and the rate of carbon dioxide production ($\dot{V}CO_2$), with linear increases in power output and $\dot{V}O_2$ respectively, and a decline in the change in end-tidal O_2 tension ($\Delta PETO_2$) with no change in end-tidal carbon dioxide tension ($PETCO_2$; (Wasserman, Whipp, Koysl, & Beaver, 1973; Whipp, Davis, Torres, & Wasserman, 1981)). These non-linear increases in ventilatory parameters were originally proposed to occur due to exercise intensity being sufficiently high that ATP turnover cannot be instantaneously supported by the mitochondria alone. Consequently, anaerobic glycolysis was, controversially, proposed to meet the ATP deficit, resulting in acidosis of the muscle (and blood). Plasma bicarbonate (HCO_3^-) would buffer the accumulating free hydrogen (H^+) ions before splitting to water (H_2O) and carbon dioxide (CO_2). This 'additional' or 'excess' CO_2 could be detected in pulmonary $\dot{V}CO_2$ and was believed to be causally linked to blood lactate accumulation and thus the LT (Wasserman et al., 1973) . However, while GET

and LT are strongly correlated with one another, the relationship is coincidental rather than causal (Gaesser & Poole, 1986; Poole & Gaesser, 1985).

A local muscle hypoxaemia and thus an O₂ demand vs. supply mismatch was originally proposed as a likely mechanism for the observed non-linear increases in V_E and $\dot{V}CO_2$ as exercise intensity increased past a certain point (Wasserman et al., 1973). It was later demonstrated that even at maximal exercise intensities, the PO₂ within the muscle is maintained sufficiently high as to not impair mitochondrial function (Connett, Honig, Gayeski, & Brooks, 1990; Wittenberg & Wittenberg, 1989) and thus oxidative ATP resynthesis will remain high and the muscle cannot be claimed to be O₂-deprived (Spurway, 1992). Based on some evidence (Busse, Maassen, & Konrad, 1991) which presented the V_E, [Bla] and plasma potassium concentration ([K⁺]) in response to incremental exercise in both the glycogen depleted and glycogen replete conditions, the pulmonary V_E responses observed during incremental exercise appear to be more likely causally linked to plasma [K⁺] than to [Bla] (Spurway, 1992). What this data clearly demonstrates is the evidently coincidental, rather than causal link between LT and GET. Furthermore, LT is more affected by glycogen depletion than GET, with LT becoming markedly elevated and the non-linear increase in V_E occurring sooner during incremental exercise (Hughes, Turner, & Brooks, 1982). Finally, while both GET and LT respond positively to exercise training, LT appears to respond more markedly (Gaesser & Poole, 1986). Due to GET providing a reliable metabolic threshold (Caiozzo et al., 1982; Davis, Frank, Whipp, & Wasserman, 1979; Powers, Dodd, & Garner, 1984) and being identifiable non-invasively, during a single, ramp-incremental exercise test, this parameter will be used throughout this body of work in favour of the LT. The next physiological 'landmark' or threshold on the exercise intensity spectrum (working from low-to-high intensity) is the maximum lactate steady state.

1.4. Maximum Lactate Steady State

As the terminology suggests, the maximum lactate steady state (MLSS) represents the highest blood lactate concentration that may be stabilised and maintained during exercise (Pringle & Jones, 2002). It represents the highest exercise intensity at which equilibrium may be reached between lactate production and lactate removal (Dotan, 2012) and typically occurs between 70 and 85 % $\dot{V}O_{2max}$ (Baron et al., 2008; de Lucas, Dittrich, Junior, de Souza, & Guglielmo, 2012; Dekerle, Baron, Dupont, Vanvelcenaher, & Pelayo, 2003; Dittrich, de Lucas, Beneke, & Guglielmo, 2013; Greco, Carita, Dekerle, & Denadai, 2012; Grossl, de Lucas, de Souza, & Guglielmo, 2012; Pringle & Jones, 2002), showing evidence of trainability (Trained: 83 ± 7 ; untrained 77 ± 5 % $\dot{V}O_{2max}$ (Greco et al., 2012)). Many methods have been proposed and adopted to determine the MLSS ranging from the classic multiple 30-min constant-power exercise tests (Pringle & Jones, 2002) through to newer 'reverse' protocols designed to ascertain the point at which [Bla] begins to decline in response to diminishing power output (Dotan, 2012). Some debate exists between whether or not the MLSS rather than the CP represents the pivotal 'threshold' above which physiological homeostasis may not be attained (Jones et al., 2010; Poole et al., 1988; Pringle & Jones, 2002). Certainly there is a strong correlation between MLSS and CP ($r = 0.95$; (Pringle & Jones, 2002); $r = 0.99$ (Greco et al., 2012)) although the CP is consistently a higher intensity than that of the MLSS (Greco et al., 2012; Pringle & Jones, 2002). This disparity in magnitude of the two 'thresholds' has sparked much of the debate as to which parameter (the CP or the MLSS) pertains to differentiation between sustainable and non-sustainable exercise intensities.

Some of the disparity may come from both the calculation of the CP and the method used to ascertain the MLSS. The methods used to determine the CP will be discussed later but briefly, the duration of exhaustive predicting trials and the mathematical model adopted for its calculation affect the parameter magnitude (Bishop, Jenkins, & Howard, 1998; Bull, Housh, Johnson, & Perry, 2000; Gaesser, Carnevale, Garfinkel, Walter, & Womack, 1995). The

'conventional' MLSS determination protocol requires the completion of three or more, 30-min, square-wave, constant-power exercise trials. The first two trials are usually imposed at power outputs (or running velocities) equivalent to just above the GET and \sim half of the difference between GET and $\dot{V}O_{2max}$. A third (or additional) trial is employed, making small changes (up or down) to the power output imposed based on the physiological responses ($\dot{V}O_2$, V_E , [Bla], HR) observed in the preceding trials. This process ceases when a power output has been determined which results in an increase in [Bla] of less than 1.00 mmol/L between min 10 and min 30 of the exercise trial (Hauser, Bartsch, Baumgartel, & Schulz, 2013; Jones & Doust, 1998; Pringle & Jones, 2002). While this criteria will provide a reasonably reliable power output and $\% \dot{V}O_{2max}$ value at MLSS, the absolute magnitude of the steady state [Bla] value within the same participant is somewhat variable between days (CV = 17 %; (Hauser et al., 2013) bringing into question the efficacy of measuring such a variable. Furthermore, the completion of multiple 30-min exercise tests at the most challenging intensity the body can sustain for 30 minutes is time consuming and requires a high level of motivation from participants. While the outcome (the absolute and relative exercise intensities) may be very useful for exercise research normalisation or training prescription, the benefit is likely outweighed by the 'cost' of time, effort and consumable requirements, certainly compared to the relatively less demanding alternative – CP determination. Furthermore, as acknowledged by Pringle & Jones (2002), in some of the MLSS exercise trials, which were at power outputs too high for a steady-state blood lactate to be attained, volitional exhaustion was reached without the attainment of $\dot{V}O_{2max}$. This observation is not in isolation (Baron et al., 2008) and poses some questions around the importance of the MLSS in characterising different physiological responses above and below the 'threshold'. Indeed, numerous investigations have examined the limit of tolerance while exercising 'at' MLSS intensity. The consensus of tolerable duration appears to be between \sim 55 and 65 min (Baron et al., 2008; Billat, Sirvent, Lepretre, & Koralsztein, 2004; Dittrich et al., 2013; Grossl et al., 2012). The reason(s) for reaching exhaustion at MLSS are not well understood, particularly as neither cardiovascular, blood acid-base or thermoregulatory responses approach their nadirs (Baron et al., 2008). Baron and colleagues have thus suggested that a central regulation of exercise cessation may be implicated.

1.5. Central (nervous system) Fatigue

While the body of work within this thesis will be concerned with exercise performance and peripheral muscle fatigue occurring over durations spanning ~ 2 min up to ~ 45 min, it would be remiss not to acknowledge the existence of and the profound effects central fatigue can have on muscle performance. Central fatigue is defined as a progressive reduction in muscle activation by the central nervous system (Gandevia, 2001). There are many proposed 'models' of muscle fatigue which originate outside of the muscle itself, including psychological/motivational and central governor models (St Clair Gibson et al., 2006). Both models share some similarities in that the brain has the ability to down-regulate the force output of the muscle based on sensory, vicarious or muscle afferent feedback (Abbiss & Laursen, 2005; Amann, 2011). The key difference between these two models however, is that the psychological model down-regulates muscle force based on lack of motivation to execute or continue a task, whereas the central governor model down-regulates muscle activity so as to avoid a physiological catastrophe or death due to the muscle/organs moving too far from homeostasis (Abbiss & Laursen, 2005). For example, knowledge of task end point has been suggested to alter pacing strategy so that the task can be completed with the best performance but whilst also avoiding fatigue (Ulmer, 1996). The same 'pacing' phenomenon occurs under the central governor model, however, it is termed teleoanticipation; it is believed to involve afferent feedback from the periphery to the central nervous system and a concomitant reduction in central motor drive in an attempt to maintain physiological homeostasis (Abbiss & Laursen, 2005; St Clair Gibson & Noakes, 2004). There is now a wealth of good experimental evidence linking the fatigue state of the muscle with a reduced central motor drive from the nervous system, and subsequently, a reduced exercise performance (Amann, 2011). However, it should be noted that while it is difficult to separate peripheral and central fatigue or explore them independently, when exercise intensity is sufficiently high as to cause exhaustion in \leq ~ 20 min, peripheral muscle fatigue is believed to predominate (Decorte, Lafaix, Millet, Wuyam, & Verges, 2012; Millet &

Lepers, 2004; Thomas et al., 2014) and as such, central fatigue will not be the main focus of this thesis.

1.6. Exercise Intensity Domains

As a muscle or series of muscles (e.g. dynamic exercise) act at a constant force and rate, several physiological systems respond in an attempt to maintain homeostasis and meet the muscles' energetic requirement. However, the physiological response to muscle action varies distinctly, dependent upon the intensity of the muscle action. It is this observation during constant-power, predominantly 'aerobic' exercise that has given rise to 'exercise intensity domains'. Broadly, exercise intensity can be categorised into four discrete intensity domains; moderate-, heavy-, severe- and extreme-intensity exercise (Barstow & Mole, 1991; Linnarsson, 1974; Whipp & Wasserman, 1972; Wilkerson, Koppo, Barstow, & Jones, 2004). Moderate-intensity exercise constitutes all exercise intensities below the GET (Poole & Richardson, 1997). Above the GET, but below the $\dot{V}O_{2max}$ and where a steady-state is observed for both $\dot{V}O_2$ and [Bla], exercise is within the heavy-intensity domain (Poole & Richardson, 1997). As soon as a sub-maximal physiological steady state is not attainable, exercise is classified as severe-intensity with a key characteristic being the attainment of $\dot{V}O_{2max}$, providing a 'maximal' effort is given by the participant (Burnley & Jones, 2007). Exercise intensities sufficiently high as to induce exhaustion prior to the attainment of $\dot{V}O_{2max}$ are classified as extreme-intensity (Hill, Poole, & Smith, 2002; Hill & Stevens, 2005; Poole & Richardson, 1997). Different terminology appears in the literature for certain intensity-domains (e.g. the use of very-heavy to describe severe-intensity and the use of severe to describe extreme-intensity exercise; (Ferguson et al., 2007; Ozyener, Rossiter, Ward, & Whipp, 2003)). Within the body of this thesis exercise intensities/domains will be referred to using the terminology and associated descriptions below.

1.6.1. Moderate-intensity

Moderate-intensity exercise includes all exercise intensities below the GET. There is a linear relationship between $\dot{V}O_2$ and power output up until exercise

intensity breaches the GET (Ozyener, Rossiter, Ward, & Whipp, 2001). Therefore, the GET demarcates the boundary between moderate- and heavy-intensity exercise. Within the moderate-intensity domain the $\dot{V}O_2$ response to constant-power exercise exhibits three phases; phase I, the cardiodynamic phase, which represents an increase in cardiac output. Phase II describes the mono-exponential rise in $\dot{V}O_2$, reflecting muscle O_2 uptake (Jones & Poole, 2005). Here $\dot{V}O_2$ rises with a time constant (τ) of ~ 45 s and a gain term typically between 9 to 11 ml.W⁻¹.min⁻¹ (Gaesser & Poole, 1996). Phase III represents the attainment of a physiological 'steady-state' which in healthy individuals (τ of ~ 45 s) is typically attained within ~ 2 to 3 minutes (Gaesser & Poole, 1996; Jones & Poole, 2005). A similar response is observed in [Bla] also, whereby after a transient increase in [Bla] shortly after the imposition of an external power output, [Bla] returns to approximately resting concentrations within 2 to 3 minutes (Jones & Poole, 2005).

1.6.2. Heavy-intensity

The heavy-intensity exercise domain exhibits very similar attributes to that of the moderate-intensity domain. However, within the heavy domain there is an additional $\dot{V}O_2$ 'superimposed' on the expected $\dot{V}O_2$ steady state value predicted from the sub-GET power vs. $\dot{V}O_2$ relationship (Whipp & Wasserman, 1972). This additional $\dot{V}O_2$ is termed the $\dot{V}O_2$ slow component and is thought to represent an increasing inefficiency within the exercising muscle (Jones & Poole, 2005). This decreased efficiency is believed to originate due to a progressively-increased recruitment of higher order motor units possessing poorer oxidative capacities than their lower order, type I, counterparts (Burnley, Doust, Ball, & Jones, 2002; Gaesser & Poole, 1996). The slow component is not limited to only $\dot{V}O_2$; slow components are also observed in intramuscular inorganic phosphate (P_i), H^+ and interstitial potassium (K^+) (Murgatroyd, Ferguson, Ward, Whipp, & Rossiter, 2011). The $\dot{V}O_2$ slow component within the heavy-intensity domain causes an elevated and delayed attainment of a steady-state. In doing so the dynamics of the physiological response change from a mono- (in the moderate-domain) to a bi-exponential function due to a 'second' rise in $\dot{V}O_2$ after ~ 2 to 3 min following the imposition of the power output (Gaesser & Poole, 1996; Jones & Poole, 2005). The steady-state (albeit

elevated) within the heavy domain is only achievable up to the CP, which demarcates the heavy- and severe-intensity exercise domains (Gaesser & Poole, 1996; Jones & Poole, 2005). The term 'critical' is apt because this intensity dictates whether homeostasis is attainable (heavy-intensity) or not (severe-intensity).

1.6.3. Severe-intensity

Severe-intensity exercise is typically tolerated for between ~ 2 and 45 min (Bull et al., 2000; Burnley et al., 2006a; Burnley & Jones, 2007; Poole et al., 1988). Physiological homeostasis will not occur, rather inexorable rises in $\dot{V}O_2$, P_i , H^+ and K^+ are observed, whilst other metabolites (e.g. phosphocreatine (PCr)) project toward their nadir, with exhaustion ensuing (Jones, Wilkerson, DiMenna, Fulford, & Poole, 2008). In the severe-intensity domain the relationship between power output and tolerable duration conforms to a rectangular hyperbola; the asymptote of which is the CP and the curvature constant is the W' (Hill, 1993; Jones et al., 2010). For the purposes of explanation, the W' represents a fixed magnitude of work that can be performed above the CP; it can be expended quickly at intensities high above CP or expended more slowly at intensities slightly above the CP (Fukuba et al., 2003). The $\dot{V}O_2$ slow component is again evident within this exercise intensity domain, but in contrast to heavy-intensity exercise, where a steady-state is attained, during severe-intensity exercise, it is the $\dot{V}O_2$ slow component that drives $\dot{V}O_2$ towards its maximum (Poole & Richardson, 1997; Poole et al., 1988). Other metabolites (P_i , H^+ and K^+) continue to rise inexorably until exercise is terminated (Jones et al., 2008; Vanhatalo, Fulford, DiMenna, & Jones, 2010a). The upper limit of the severe-intensity domain was thought to be the $\dot{V}O_{2max}$ but this has been challenged (Hill et al., 2002; Hill & Stevens, 2005). The upper limit of the severe intensity domain is in fact more difficult to demarcate; the fourth intensity domain is a relatively recent concept compared with the preceding three domains.

1.6.4. Extreme-intensity

The extreme intensity domain encompasses intensities of exercise, which are sufficiently high that exhaustion occurs before the $\dot{V}O_{2max}$ is attained. Typically

these are exercise durations of ≤ 150 s, depending on the speed of the $\dot{V}O_2$ kinetics of the participant (Hill & Stevens, 2005). Due to the difficulty in stipulating an exercise intensity representing $\dot{V}O_{2max}$ ($\dot{V}O_{2max}$ being attained at a range of power outputs, i.e. any power output within the severe-intensity domain), providing a normalised 'threshold' indicating the lower-bound of the extreme domain proves difficult. Those that have attempted this have reported 117 to 136 % of power associated with the attainment of $\dot{V}O_{2max}$ during a step-incremental exercise test to volitional exhaustion (Caputo & Denadai, 2008; Hill et al., 2002).

Appreciation of the distinct physiological response characteristics across exercise intensities provides support that when comparing the effects of a given external power output across human participants, care should be taken to ensure exercise is set relative to the physiological thresholds which determine exercise intensity domains.

1.7. Normalising Exercise intensity

As detailed above, the physiological response to exercise either side of a 'threshold' can be quite distinct. Therefore, when attempting to prescribe exercise across different human participants, which elicits the same physiological response and characteristics, these physiological 'thresholds' must be taken into account (Burnley & Jones, 2007). Surprisingly, given the plethora of evidence describing physiological responses below and above a number of metabolic thresholds, the most common method of setting exercise intensities across participants remains as a $\% \dot{V}O_{2max}$ (Burgomaster, Hughes, Heigenhauser, Bradwell, & Gibala, 2005). Typically, at intensities of ~ 100 $\% \dot{V}O_{2max}$, similar physiological responses and exercise tolerance are observed between participants (Ozyener et al., 2003). However, as exercise intensity decreases below $\dot{V}O_{2max}$, for example, intensities between ~ 50 to 70 $\% \dot{V}O_{2max}$, the physiological and perceptual response to exercise becomes much more varied (Burgomaster et al., 2005). This is expected, given that GET can occur between ~ 50 to 75 $\% \dot{V}O_{2max}$ (Gaesser & Poole, 1986; Spurway, 1992). Thus exercise at 60 $\% \dot{V}O_{2max}$ for a participant with a GET occurring at 50 $\% \dot{V}O_{2max}$

will be more 'taxing' than it will be for a participant with a GET at 70 % $\dot{V}O_{2max}$ (Burnley & Jones, 2007). However, if both the intensity at the GET and that of the $\dot{V}O_{2max}$ are taken into account when setting a constant-power exercise intensity, the physiological responses across participants becomes much more uniform (Casaburi, Storer, Ben-Dov, & Wasserman, 1987; Ozyener et al., 2001, 2003; Roston et al., 1987).

At exercise intensities of 80 to 90 %GET, a similar physiological response will be observed independent of who performs the exercise or what the absolute magnitude of the external power output is. For example a healthy human and an elite athlete with a GET of 50 and 300 W respectively will exhibit a mono-exponential increase in $\dot{V}O_2$, achieving a steady-state within 2 to 3 minutes, with accompanying steady-state conditions observed in HR, [Bla] and P_i irrespective of the 200 W difference in absolute power output at 80 %GET. Above the GET, this approach is concerned with the relative occurrence of the GET and $\dot{V}O_{2max}$ and has thus been termed the 'delta concept' (Ozyener et al., 2001, 2003). For example, 40 %delta (40 % Δ) would be equal to 40 % of the difference in $\dot{V}O_2$ or power output between GET and $\dot{V}O_{2max}$, plus the ($\dot{V}O_2$ or power output at) GET (Ozyener et al., 2001). A power output or $\dot{V}O_2$ of 40 % Δ would very likely result in a physiological response whereby a 'steady-state' (albeit delayed) $\dot{V}O_2$ would be attained, with exercise being tolerable for up to ~ 3 to 4 hours (Burnley & Jones, 2007; Ozyener et al., 2001). Whereas, at an intensity of 80 % Δ , it is likely that homeostasis in $\dot{V}O_2$ would not be attained, instead with $\dot{V}O_2$ projecting toward its maximum and exercise tolerance lasting only a number of minutes (Bailey, Wilkerson, Dimenna, & Jones, 2009b; Bailey et al., 2009c; Burnley, Davison, & Baker, 2011; Ozyener et al., 2001). The delta concept provides a stronger rationale for setting relative exercise intensities compared with simply % $\dot{V}O_{2max}$; certainly up to ~ 50 % Δ where most participants will exhibit very similar physiological responses to constant-power exercise. However, once a second, higher intensity threshold is breached (the maximal lactate steady state or the CP – see previous sections 1.4 and 1.6), exercise intolerance becomes more divergent between participants for a given % Δ (Bailey, Vanhatalo, Wilkerson, Dimenna, & Jones, 2009a; Bailey et al., 2009c). This increased variability of exercise tolerance at power output above ~ 50 % Δ is due to a 'shift' in the origin of muscle fatigue from a predominantly centrally-

limited exercise tolerance toward peripheral muscle fatigue (Amann, 2011; Pringle & Jones, 2002). This does limit the utility of the delta concept at higher $\% \Delta$ power outputs but this method is still far superior to simply $\% \dot{V}O_{2max}$, even at high $\% \Delta$. Furthermore, no additional exercise tests are required in order to obtain the parameters required for calculating $\% \Delta$.

Whipp and colleagues presented the utility of a simple ramp-incremental exercise test in the early 1980s (Whipp et al., 1981). While the specific protocol has changed with advancements in equipment, the fundamental principles of the incremental test have continued to be employed in the determination of the GET and $\dot{V}O_{2max}$ in recent exercise physiology literature (Burnley et al., 2006a; Vanhatalo et al., 2007; Vanhatalo, Doust, & Burnley, 2008a, 2008b). A similar ramp incremental test will be used within this body of work to determine both the GET and $\dot{V}O_{2max}$.

1.8 Validity and Reliability

For clarity, a number of definitions (and where appropriate examples) will be given here with regard to a number of terms used within this body of work.

1.8.1. Validity

Validity can be used in the description of how well a scientific methodology answers the question it set out to and then how the results apply in a 'real world' situation (ecological validity). While the term validity can have a breadth of meaning, within this body of work, validity is used to describe the degree to which a measurement tool (e.g. the 3-min all-out cycling test) measures what it is supposed to measure (e.g. the CP and W' of the P-D relationship). If the measurement from a tool does not provide an accurate measure, it is not valid. It should be noted that there is no statistic for validity, thus, the validity of a measure is subject to a degree of interpretation. A measure should provide results that are (statistically) not different to a criterion to be considered valid.

1.8.2. Reliability

Reliability is concerned with the consistency of a measure. A measure (e.g. all-out derived P-D parameters) is considered reliable if it returns similar results when repeated under consistent conditions.

1.8.3. Resilience

Resilience is concerned with the ability to return to an original form or state following an interference or disturbance to that form or state. For example, a muscle can be considered resilient to fatigue because given a period of rest, a muscle will function 'like new' despite having previously been fatigued.

1.8.4. Sensitivity

Sensitivity refers to the ability of a test to correctly identify the 'true' result. A sensitive test has the ability to correctly determine the known result. For example if a test was 100 % sensitive, it would always correctly identify the known result. Conversely, if a test was 0 % sensitive it would never identify the correct result and would be effectively useless; a better test would be required.

1.8.5. Precision

Precision of a measurement is concerned with the reproducibility of that measure when repeated. For the purposes of this thesis, reliability will be used in favour of precision but the two definitions could be used interchangeably.

1.8.6. Accuracy

Represents the degree of closeness of a measure to the known 'true' value. Again, for the purposes of this thesis, validity will be used in favour of accuracy, but practically, these two words (validity and accuracy) could be used interchangeably.

A measure can be: (i) valid but not reliable; (ii) reliable but not valid; (iii) neither valid nor reliable and; (iv) both valid and reliable. Clearly the latter is desirable. Reliability in a measurement without accuracy can be accounted for with a calibration equation (Hopkins, 2010). However, without reliability, a measure is of limited use.

1.9. Direction

This body of work aims to extend the use of the CP concept applied to all-out exercise through the use of a novel, 3-min all-out exercise test. In doing so, greater experimental ground will be covered enabling both 1) further validation of the 3-min all-out test when deployed under conditions it has yet to be used and, 2) the gain of greater insight into the physiological underpinnings of the W' parameter of the P-D relationship for severe-intensity exercise.

The following review of the literature will outline (i) the limitations to high-intensity exercise tolerance, and (ii) the currently established and putative mechanisms of altering both the CP and W' parameters. This review will highlight the importance of the P-D relationship in characterising exercise performance and form hypotheses which can be uniquely tested through the use of the 3-min all-out cycling test, with specific focuses on: 1) the effect of prior severe-intensity exercise on the magnitude of the W' ; 2) the effect of muscle glycogen content on both the CP and W' ; 3) the effects of hypoxia on the CP and W' and; 4) the influence of exercise training on the CP and W' .

Chapter 2 - Literature Review

2.1. The Critical Power Parameter

Mathematically, the CP represents the highest exercise intensity or power output that can be maintained indefinitely, in the absence of fatigue (Monod & Scherrer, 1965). However, this theoretical simplification fails to account for numerous physiological responses to exercise such as substrate availability, thermoregulation and central fatigue processes (Jones et al., 2010; Poole et al., 1988). The CP does however, demarcate the heavy- and severe-intensity exercise domains with exercise below the CP resulting in the attainment of a steady state in oxygen uptake and other physiological entities such as P_i , $[Bl_a]$, pH and creatine (Cr) (Jones et al., 2008; Poole et al., 1988). Some investigators have not reported the attainment of a steady state when exercising 'at' CP (Brickley, Doust, & Williams, 2002). The methods used to determine the CP (and W') can have subtle, but profound effects on the subsequent responses to exercise *at*, below and above this 'critical' exercise intensity (challenges in the accurate determination of CP are discussed subsequently – sections 2.2.5 & 2.2.7). In practice, exercise *at* CP can be sustained for between ~ 20 and ~ 90 min (Hill, 1993; McLellan & Cheung, 1992; Overend, Cunningham, Paterson, & Smith, 1992; Vanhatalo et al., 2007). As the CP intensity represents the maximal rate at which ATP can be resynthesised via aerobic means for the performance of muscular work, it is presumed to represent an inherent characteristic of oxidative metabolism (Gaesser & Wilson, 1988; Jones et al., 2010). The CP can be increased with exercise training (Gaesser & Wilson, 1988; Poole, Ward, & Whipp, 1990; Vanhatalo et al., 2008a) and hyperoxic gas inspiration (Vanhatalo et al., 2010a), decreased with hypoxic gas inspiration (Dekerle, Mucci, & Carter, 2012; Moritani, Nagata, deVries, & Muro, 1981), high pedal rates (Carnevale & Gaesser, 1991) and following blood donation (Burnley, Roberts, Thatcher, Doust, & Jones, 2006b). The following sections will outline how the CP and W' are mathematically derived, their ability to predict severe-intensity exercise tolerance and the putative underpinning physiology of both parameters.

2.2. Conventional Methods of Determining the CP and W'

The 'gold standard' methodology for CP and W' determination involves the imposition of a series of 3 to 7 different, severe-intensity power outputs each on a separate day (Hill, 1993; Jones et al., 2010). Participants must sustain the imposed power for as long as they can tolerate on each occasion. Time to exhaustion (T_{lim}) and power output are recorded and together used to model an individual's P-D relationship, yielding both the CP and W' parameters. There are a number of models that can be used to calculate the CP and W' parameters from the power and exhaustion time data; these are detailed in sections 2.2.1 to 2.2.4 and summarised in section 2.2.5. While other methodologies of determining the P-D parameters are available (e.g. fixed-duration 'time-trial' bouts), time to exhaustion trials are amongst the most reliable in determining the CP & W' parameters (Hinckson & Hopkins, 2005). Times to exhaustion across a range of severe-intensities (durations ranging from 1.8 to 7.8 min) varied by between 9 and 16 %. The variability in CP (or specifically critical velocity) within participants was 1.8 % and in W' (or specifically 'distance prime') was 14 % (Hinckson & Hopkins, 2005).

2.2.1. 2-parameter CP model

1) Non-linear, hyperbolic model:

The natural form of the P-D relationship is a rectangular hyperbola with horizontal asymptote at time = 0 and vertical asymptote power = CP. Tolerable duration possible at a given constant-power is represented by:

$$\begin{aligned}t &= W'/(P-CP) && [2.1] \\P &= (W'/t)+CP\end{aligned}$$

Where t = time or tolerable duration, and P = constant-power output (Gaesser et al., 1995; Whipp, J., Stoner, Lamarra, & Wasserman, 1982a).

2) Linear, power vs 1/time model.

While the power-duration (P-D) relationship is hyperbolic, by expressing power against the inverse of time, the relationship becomes linear (Equation 2.2).

$$t = 1/((P - CP)/W') \quad [2.2]$$
$$P = CP + (W' \times 1/t)$$

Where P is the power output or exercise intensity that is sustainable for a given time (t). In the Power vs. 1/t model the W' represents the slope of the linear relationship and the CP the y-intercept (Gaesser et al., 1995; Jones et al., 2010).

3) Linear, work vs. time model

A second method of expressing the P-D relationship linearly is to plot work done against duration of exhaustive predicting trial. Here, the y-intercept represents the magnitude of the W' and the slope of the relationship is the CP (Monod & Scherrer, 1965).

$$t = (W-W')/CP \quad [2.3]$$
$$W = W' + (CP \times t)$$

Where W is work done (the product of P·t; (Gaesser et al., 1995; Monod & Scherrer, 1965; Wilkie, 1960)).

When at least three predicting trials are used to obtain CP and W' parameter estimates, all models provide 'goodness of fit' parameters (namely the R² and the SEE) which can be used to determine which model provides the highest agreement between the exercise trials used to estimate the P-D parameters. It is common to accept CP and W' parameter estimates from the model providing the greatest linearity (R²) and the least 'error' (SEE) around both CP and W' parameter estimates (Hill, 1993). In the few published examples of reliability of the CP and W' parameters, the CP parameter shows a test-retest correlation coefficient of between 0.92 (Hill & Smith, 1993) and 0.96 (Gaesser & Wilson,

1988) with the W' correlation coefficients being between 0.64 (Smith & Hill, 1993) and 0.87 (Nebelsick-Gullett, Housh, Johnson, & Bauge, 1988). Coefficient of variation (CV) data for the CP and W' are presented in Table 2.2 p49.

2.2.2. 2-Parameter critical power model assumptions

As the CP model is a simplified mathematical parameterisation of a human bioenergetic system, there are a number of assumptions inherent to its applicability (Morton, 2006):

- 1) The CP parameter is rate-limited (by maximum sustainable 'aerobic' ATP resynthesis) yet has unlimited 'capacity'

The assumption that ATP can be indefinitely provided at the rate equivalent to the CP is clearly untrue. Since oxidative phosphorylation requires energy substrate which would become limiting in any human in extreme circumstances (e.g. extremely prolonged exercise (> several days), or starvation). Therefore, there is some form of 'capacity limitation' to the CP. Furthermore, experimental evidence suggests that exercise at the CP (which should be unlimited) is tolerated typically for between ~ 20 to 60 minutes (Brickley et al., 2002; Bull et al., 2000; McLellan & Cheung, 1992). However, the assertion that the CP is rate-limited is well established (Poole et al., 1988). Independent of terminology, an upper limit of sustainable power output exists and there is a 'rate-limited' upper limit.

- 2) The W' is 'capacity' limited but not rate limited

It is reasonable to assume that the 'anaerobic' supply component of the CP model is capacity limited owing to the supposition that the W' comprises a high-energy phosphate store (PCr), muscle glycogen for use in anaerobic glycolysis and a small, myoglobin-bound O_2 store (Moritani et al., 1981; Poole et al., 1988). Conversely, if considering the W' as a 'store' which becomes filled (rather than a depleting 'store') with severe-intensity exercise, then the capacity is limited by the tolerable quantity of H^+ , K^+ and P_i which can accumulate (Ferguson et al., 2010). However, the rate-unlimited aspect of this assumption is over-simplified. It suggests that power outputs in excess of the peak

mechanical power output (PPO) can be achieved based on there being adequate energy supply to do so. Or perhaps a simpler example to illustrate the point, the assumption is made that a human can achieve a running speed of more than 13 m/s instantaneously (Morton, 2006). Obviously this is not possible as some time would be taken to achieve such a speed and in doing so, there must then be an element of 'rate limitation'.

3) Exercise may continue for as long as energy supply is sufficient to meet energy demand

This assumption effectively states that at the full expenditure of the W' , exercise must cease. The physiological determinants of the W' will be discussed later (section 2.6. the curvature constant (W') of the P-D relationship) but if for example muscle glycogen comprises some of the W' then it is quite apparent that exhaustion often occurs well before muscle glycogen stores are emptied, and in fact the sooner exhaustion occurs (higher power outputs), the more muscle glycogen that remains (Saltin & Karlsson, 1971). Based on this, it has been suggested that the CP model may result in under predictions of the available 'anaerobic energy' (Morton, 2006). However, when W' is assumedly fully expended, exercise may continue provided the exercise intensity is substantially reduced (Coats et al., 2003). In this sense, assumption 3) holds true in that exercise can only continue when energy supply can meet energy demand.

4) At exercise onset, 'aerobic power' is instantaneously available up to its maximum rate (CP) through to exercise termination

Assumption 4) is clearly flawed as evidenced since the early work of Krogh & Lindhard (1920) and Hill & Lupton (1923) right through to more recent times (Burnley & Jones, 2007). At exercise onset, oxygen uptake increases mono-exponentially with a τ of ~ 45 s, reaching a steady-state (at intensities below the GET) in 2 to 3 minutes (Gaesser & Poole, 1996). During this transient increase in oxygen uptake and presumably 'turning on' of the aerobic machinery (Bishop et al., 1998), the energy demand of the abrupt transition to an exercise intensity would appear to be met (at least in part) by the 'anaerobic' system, or in the case of the CP model, the W' . Once again it has been reasoned that if this initial

contribution from the W' at exercise onset is not 'accounted for' then the W' may be underestimated (Morton, 2006).

5) The power range over which the CP model applies encompasses all powers above CP through to infinity

As noted under assumption 2) the power range over which the CP model can be applied must have an upper limit; the PPO. It is not humanly possible to produce concentric power in excess of PPO, irrespective of what the CP model may suggest. At the other end of the intensity spectrum, exercise at power outputs below the CP derive all of the required energy supply from oxidative sources, which, according to assumption 4) are available instantaneously at exercise onset, and thus the W' remains untouched. In reality this is likely not the case, but there is now strong evidence to suggest that (providing exercise is maintained in the heavy- or moderate-intensity domains) W' is replenished (Skiba, Chidnok, Vanhatalo, & Jones, 2012).

6) The duration range over which the CP model applies covers time 0 s to infinity

As addressed in assumption 1), exercise cannot be maintained indefinitely, even when below the CP, due to fuel availability and thus energy supply limitations. Furthermore, at exercise intensities below the CP, causes of fatigue, exhaustion or exercise termination become less clear and may range from boredom, mental fatigue, central fatigue or simply practical reasons (i.e. the need to void; (Abbiss & Laursen, 2005; Amann, 2011; Morton, 2006)). Again, at the other end of the intensity spectrum, very high power outputs should result in very short T_{lim} . Theoretically speaking, any attempt to produce or sustain a power output of or in excess of PPO would result in an endurance time of zero (Morton, 2006).

7) CP and W' are constants unaffected by power output or exercise duration

While there is evidence that both the CP and W' can, and will, be manipulated by various chronic and acute interventions (detailed throughout this thesis), if examined under the same conditions day after day, they appear to show good consistency (CV for CP typically less than $\sim 3\%$ and W' less than $\sim 5\%$

(Ferguson et al., 2010; Ferguson et al., 2007)). Indeed, without this assumption, it becomes very difficult to experimentally explore the CP and W' parameters individually or the P-D relationship as a whole (Morton, 2006).

8) The efficiency of converting chemical energy to mechanical energy remains constant across power and duration ranges

At present it is not possible to ascertain muscle efficiency at power outputs higher than CP due to non-steady-state metabolic conditions (de Koning et al., 2013; Noordhof, Vink, de Koning, & Foster, 2011). As such, there is little direct information about muscle efficiency across the power and duration spectrum of the CP model. It would appear that muscle efficiency may not remain constant across the severe-intensity domain and may be 'worsened' by an all-out pacing strategy (Vanhatalo, Poole, DiMenna, Bailey, & Jones, 2011). Certainly when outside of the laboratory, energy cost per unit speed is not linear with faster cycling speeds requiring disproportionately more power output to sustain (Martin, Gardner, Barras, & Martin, 2006). This non-linearity when outside of the laboratory could be built into the CP model but in doing so the model would become somewhat more cumbersome (Morton, 2006).

Summary

Despite some limitations due to model assumptions, the CP model provides a very simple method of understanding human exercise performance capabilities (at least in a laboratory setting). An appreciation of some of the limitations to the model is necessary in interpreting input and output from that model but due to the utility of the 2-parameter CP model to depict exercise tolerance over a range of power outputs, it becomes an attractive template with which to explore the determinants of the CP and W' parameters.

2.2.3. 3-parameter CP model

The 2-parameter CP model is popular due to its simplicity and ease of use. However, as highlighted above in assumption 5) & 2), the model assumes it is possible to utilise the W' instantaneously for a duration of 1 s or less; i.e. it is possible to produce power outputs well in excess of PPO. The 3-parameter CP

model attempts to address this issue by taking account of the mechanical peak power output (P_{\max}) by setting P_{\max} as the y-axis intercept of the P-D hyperbola (Gaesser et al., 1995; Morton, 1986).

$$t = (W'/(P-CP)) - (W'/(P_{\max}-CP)) \quad [2.4]$$

$$P = (W'/(t - (W'/(CP - P_{\max}))) + CP$$

Where P_{\max} represents the maximal mechanical power output attainable with a maximal effort initiated from a fully rested state. This additional parameter greatly improves the predictive capacity of the CP model for shorter-duration performances (~ 0 – 120 s) compared with the 2-parameter model. Indeed, the poor predictive capacity of the 2-parameter model over short-duration exercise (< 60 s) led to the development of an exponential model (Hopkins, Edmond, Hamilton, Macfarlane, & Ross, 1989). While this model may have better characterised the performance capabilities over short-duration exercise bouts, it has yet to be validated in the literature for its CP estimates.

2.2.4. Exponential model

Hopkins et al. (1989) developed an exponential model to predict CP and characterise exercise tolerance over short duration (≤ 3 min) inclined treadmill running. The iterative least-squares procedure fit data between two points (T_{lim} trials) using an exponential time constant value. This process does not provide an estimate of W' but does provide both a CP and a P_{\max} estimate (Gaesser et al., 1995; Hopkins et al., 1989):

$$P = CP + (P_{\max} - CP) \exp^{-t/\tau} \quad [2.5]$$

2.2.5. Influence of mathematical model on CP & W'

A number of publications have compared the CP and W' parameter estimates using the above 5 predictive models (Bull et al., 2000; Gaesser et al., 1995). Consistently the CP estimates differ across models, with the following models providing CP estimates in order of high to low CP (summarised in Table 2.1

p40); exponential model ([2.5]), linear Power Vs. 1/t ([2.2]), linear work vs. t ([2.3]), 2-parameter non-linear ([2.1]) and 3-parameter non-linear ([2.4]) (Bull et al., 2000; Gaesser et al., 1995). The W' estimates of the four models providing this parameter (exponential model does not estimate W') ranked in the opposite order with the 3-parameter non-linear model estimating W' to be ~ three fold larger than the two linear (power vs. 1/t & work vs. t) models (Gaesser et al., 1995). Although the 3-parameter non-linear model consistently provides the lowest estimate of CP, this estimate was not different to an exercise intensity that can be maintained for 40 minutes with evidence of a steady-state in V_E from min 20 to min 40 (Gaesser et al., 1995). Subsequently, the CP from the 3-parameter non-linear model has proved to be sustainable for 60 min in most participants (exercise terminated at 60 minutes (Bull et al., 2000)). Based on these findings, it may be suggested that the 3-parameter non-linear model underestimates CP, and certainly appears to overestimate the W' (Gaesser et al., 1995). The non-linear 2-parameter model provides the next lowest CP estimate and a more 'realistic' W' value (Gaesser et al., 1995). However, working with linear regressions simplifies obtaining parameter estimates. Given that the linear work vs. time model sits centrally ranked in its CP parameter estimate, the close agreement with the 2-parameter non-linear model ($r=0.99$ for CP and $r=0.87$ for W' (Gaesser et al., 1995)) and the typically excellent fit (R^2) of the work vs. time model ($R^2= 0.99 \pm 0.01$), this appears to be a practical option for deriving CP and W' estimates from conventional exhaustive trials.

Table 2.1. Difference in CP & W' estimates from five mathematical models. CP and W' parameters derived from 5 different predicative models and arranged in rank order of CP value from lowest to highest prediction. Reproduced from Gaesser et al. (1995).

	CP (W)	W' (kJ)	P _{max} (W)	τ (s)	R ²
1 Three-Parameter nonlinear	195 ± 29	58 ± 19	504 ± 72		0.99 ± 0.01
2 Two-Parameter nonlinear	215 ± 24	28 ± 7			0.99 ± 0.01
3 Linear (W vs. t)	224 ± 24	22 ± 6			0.99 ± 0.01
4 Linear (P vs. 1/t)	237 ± 24	18 ± 5			0.96 ± 0.03
5 Exponential	242 ± 21		473 ± 62	249 ± 82	1.00 ± 0.01

Data are mean ± SD, n = 16

CP: 1 < 2, 3, 4, 5; 2 < 3, 4, 5; 3 < 4, 5 (all P < 0.005); 4 < 5 (P = 0.08)

W': 1 > 2, 3, 4; 2 > 4 (all P < 0.008); 2 > 3 (P = 0.08); 3 > 4 (P = 0.20)

Pmax: 1 > 5 (P = 0.15)

R2: 4 < 1, 2, 3, 5 (all P = 0.005); 2 < 1 (P = 0.26), 3 (P = 0.08), 5 (P = 0.02); 1 < 3 (P = 0.50), 5 (P = 0.23); 3 < 5 (P = 0.60)

2.2.6. Alternative exponential model

A further exponential model has been developed more recently which purports to accurately describe the performance capabilities (T_{lim}) during cycling (or running) over very short (~ 3 to 300 s) periods of time (Bundle et al., 2006; Weyand, Lin, & Bundle, 2006). This model suggests it is based upon an “anaerobic power reserve” which for simplicity would act similarly to the W'. This power reserve is effectively equal to the difference between peak mechanical power output (PPO) and the power output equivalent to $\dot{V}O_{2max}$ (P_{aer}) (Bundle & Weyand, 2012; Weyand et al., 2006).

$$P(t) = P_{aer} + (PPO - P_{aer}) \cdot e^{(-0.026 \cdot t)} \quad [2.6]$$

Where P(t) is the power output sustainable for a time (t). The model does indeed predict the powers sustainable for short durations reasonably well ($R^2 = 0.96$ between predicted and measured power output at powers between ~ 200 W and 1100 W; (Weyand et al., 2006)). While the authors of this model do make it very clear that they are interested in characterising and predicting power and duration capabilities of ‘sprint’ cycling (i.e. over short exercise durations), they also suggest that their model is accurate up to at least 350 s (Weyand et al., 2006). However, their exponential curves appear to effectively

'plateau' just after ~ 100 s (Weyand et al., 2006). Surprisingly, the power reserve model has yet to be compared against the original exponential CP model or any of the other CP mathematical models. However, while the power reserve model appears to accurately describe power and duration capabilities over constant-power trials of a few seconds up to ~ 300 s, the effective CP estimate is, like the exponential model of Hopkins et al. (1989), likely to overestimate a 'true' CP. Furthermore, there are a number of issues with the methodology which cause concern when trying to apply or compare the power reserve model to the CP concept. Firstly, and critically, the parameter P_{aer} (which is pivotal in determining the magnitude of the anaerobic power reserve) is an extrapolated value based on the submaximal Power vs. $\dot{V}O_2$ relationship. This relationship is not linear, and changes 'slope' as exercise intensity crosses intensity domains, causing the $\dot{V}O_2$ response to external power output to change (Poole & Jones, 2012; Poole et al., 1988). The authors would arguably have been better off attempting to use the CP parameter in their model as the CP effectively represents the maximum rate that energy can be resynthesised using only oxidative means (Hill, 1993; Jones et al., 2010). Secondly, despite trying to characterise the P-D relationship for 'sprint' cycling and terming their 'predictive' trials as "all-out", these trials were performed at a constant cadence (100 rpm) and a constant-power output (ensuring any changes in time to exhaustion with increased power output were a result of changes in pedal force and not contraction frequency). Thus, the exponent used in their model is likely to change (perhaps considerably) with the use of higher or lower cadences (Sargeant, Hoinville, & Young, 1981; Tomas, Ross, & Martin, 2010). Therefore, a 'one-size-fits-all' exponent is unlikely to exist for all-out cycling where cadence is able to vary as it would if exercising on a push bicycle. As a result, applying the anaerobic power reserve model to all-out exercise where cadence changes through a varied range is not currently plausible.

2.2.7. Duration of predicting trials

Historically the durations of predicting trials have been recommended to be between 1 and 15 minutes (Hill, 1993; Moritani et al., 1981). However, the duration of the trials utilised to obtain parameter estimates has a profound effect on the magnitude of each the CP and W' (Bishop et al., 1998). Elevated

estimates of the CP and suppressed estimates of the W' result when short-duration predicting trials are included in the linear model. The opposite is true of the inclusion of only 'long-duration' predicting trials; whereby the CP estimate is suppressed and the W' estimate is elevated (Bishop et al., 1998). Indeed, Bishop and colleagues suggested that predicting trials shorter than ~ 150 s would not enable the full expenditure of the W' , thus giving rise to a suppressed W' estimate. This suggestion is further supported with the observations of Hill and Stevens (2005) who show that the minimum duration of a constant-power exhaustive exercise trial in which $\dot{V}O_{2\max}$ is attained is ~ 151 s; exhaustion elicited any sooner than this is likely to not coincide with the attainment of the $\dot{V}O_{2\max}$. The non-attainment of $\dot{V}O_{2\max}$ at or shortly prior to exhaustion during constant-power exercise thus fails to meet one of the defining criteria of severe-intensity exercise, and must then be classified as extreme-intensity (Hill & Stevens, 2005; Jones & Poole, 2005). If further evidence was required as to why exhaustive predicting trials of less than ~ 150 s may not enable the full completion of work above CP equivalent to the W' , it could come from the literature exploring the maximum accumulated oxygen deficit (MAOD). While this method is fraught with assumptions and will be dealt with in section 2.10.1. ('Maximum Accumulated Oxygen Deficit (MAOD)') the global principle suggests that exercise of less than ~ 120 s is of insufficient duration to fully accumulate maximal anaerobic work (Medbo et al., 1988; Noordhof et al., 2011). More evidence is available from the data presented in the all-out exercise testing used to obtain estimates of the P-D relationship parameters (Burnley et al., 2006a; Vanhatalo et al., 2007, 2008a, 2008b). In much of the all-out literature (discussed below) it is possible to observe power output continuing to fall toward its asymptotic value up until around 150 s. Bishop et al (1998) also warned against exhaustive exercise trials which extend much past ~ 15 min in duration. They suggested that as exercise duration extends, motivation and central fatigue mechanisms have the potential to increasingly contribute to exercise termination. The CP concept describes peripheral fatigue. Naturally, this is the fatigue mechanism of interest and thus every attempt must be made to ensure the limit to exercise tolerance is due to peripheral bioenergetic consequences. Thus the guidelines on the duration of predicting trials used to obtain CP and W' estimated using conventional 2-parameter models should be between 2.5 and 15 min (Bishop et al., 1998; Hill, 1993; Jones et al., 2010).

2.3. All-Out Method of Determining CP and W'

In 2006 Burnley and colleagues introduced an all-out cycling test of 3-min duration, which purported to provide a valid estimate of the maximal steady state (i.e. the CP; (Burnley et al., 2006a)). The premise of the test is elegantly simplistic; initiate a maximal seated sprint effort, and maintain a maximal effort, for 3-minutes with no feedback regarding duration (to ensure no 'pacing' of the effort emerges). Following initial very-high power output, power begins to fall, in a pattern resembling a hyperbola, until power output attains a plateau or steady-state toward the end of the test. Initially the W' is 'expended'. Once the W' is fully 'depleted' the highest attainable power output should be that of the CP (Burnley et al., 2006a). Indeed, when the second-by-second power output data over the duration of a 3-min all-out test is reduced into average 15 s bins, power output is significantly reduced between each time bin except over the final 45 s of the test (Vanhatalo et al., 2007). The difference in power over the final 45 s of a 3-min all-out test remains very stable and becomes more stable still over the final 30 s (difference in power of 0 W, 95 % confidence limit: -4.8, 4.0 W; (Vanhatalo et al., 2007)). This suggests that the conceptual premise of the test holds true in practice and that a 3-min duration is sufficient for the full expenditure of W' and the determination of a steady-state power output (Burnley et al., 2006a; Vanhatalo et al., 2007). By taking an average of the power output over the final 30 s of the all-out test, a parameter termed end power (EP) is derived which is synonymous with the CP (Burnley et al., 2006a; Vanhatalo et al., 2007, 2008a, 2008b). The work-time integral above this end power is termed work above end power (WEP) and is synonymous with the W' (Vanhatalo et al., 2007, 2008a, 2008b).

Since the introduction of the 3-min all-out test, numerous additional experiments have confirmed that the all-out, EP and WEP parameters provide valid and reliable estimates of CP and the W' respectively (Vanhatalo et al., 2007, 2008a,

2008b). The SEE (also known as typical error; TE) of the all-out derived CP estimate has been reported between 6 and 7 W (± 2 and 3 %; (Burnley et al., 2006a; Vanhatalo et al., 2007)). The all-out W' estimate shows slightly more variability, with a correlation coefficient (assessed against W') of $r = 0.84$ and a TE of ± 2.76 kJ (~ 17 %; (Vanhatalo et al., 2007)). However, other research groups have reported larger variability in both the all-out CP estimate (CV = 6.7 %, SEE = 15 W) and the all-out W' estimate (CV = 21 %, SEE = 1.46 kJ; (Johnson, Sexton, Placek, Murray, & Pettitt, 2011)). Yet, another research group, who more rigorously followed the originally described methods of Burnley et al. (2006), have since reported CV values of 3.5 and 12.0 % for EP and WEP respectively (further reliability data for both all-out and conventional CP and W' parameters are presented in Table 2.2 p49), albeit using a 3-min all-out test as the 'criterion' measure (Constantini, Sabapathy, & Cross, 2014).

The original 3-min all-out test work (Burnley et al., 2006a; Vanhatalo et al., 2007, 2008a, 2008b) provides compelling evidence that the all-out test can validly determine the exercise intensity at which exercise becomes unsustainable; i.e. the heavy-severe-intensity exercise boundary. Furthermore, the original publications on the all-out test showed that: (i) the 3-min test tracks training-induced changes in the CP (Vanhatalo et al., 2008a); (ii) is dependent upon the correct setting of ergometer resistance for valid CP and W' estimates (Vanhatalo et al., 2008b) and; (iii) is unaffected by either a prior sprint exercise bout (with adequate recovery (Vanhatalo & Jones, 2009b)) or induced alkalosis (Vanhatalo, McNaughton, Siegler, & Jones, 2010b). Despite a successful induction of alkalosis through the consumption of $0.3 \text{ g}\cdot\text{kg}^{-1}$ body mass of sodium bicarbonate (NaHCO_3) 45 minutes prior to completing a 3-min all-out test, no differences were observed in EP, WEP or total work done during the experimental and placebo 3-min tests (Vanhatalo et al., 2010b). Furthermore, CV between experimental and placebo 3-min test parameters were reported as 3 % and 5 % for EP and WEP respectively; the most reliable reported to date (Vanhatalo et al., 2010b).

In a separate, but equally elegant investigation, Vanhatalo & Jones (2009) observed the effect of performing a prior 30 s maximal sprint followed by either 2 or 15 minutes of recovery, on the P-D parameters from the 3-min all-out test.

The randomised crossover design, including a control 3-min all-out test, revealed that the EP parameter was unaffected by the prior maximal sprint (Control: 235 ± 44 ; 2 min recovery: 223 ± 46 ; 15 min recovery: 232 ± 50 W). However, WEP was significantly reduced (as was total work done) during the 2-min recovery 3-min all-out test compared to control and 15 min recovery 3-min test (Control: 20.8 ± 3.9 ; 2 min: 16.5 ± 3.3 ; 15 min: 21.2 ± 4.5 kJ). The WEP observed in the 2 min recovery 3-min test corresponded to 79 % of the control condition WEP value. Given previous research suggesting that muscle PCr reaches ~ 80 % of resting levels 2 min after a maximal 30 s sprint (Bogdanis, Nevill, Boobis, Lakomy, & Nevill, 1995), the results of the Vanhatalo & Jones (2009) paper provide further compelling evidence that, 1) the 3-min all-out test is sensitive to detect alterations in W' induced by prior exercise $> CP$ and, 2) that the putative physiological underpinnings of the CP and W' appear to be correct.

Vanhatalo et al. (2008a) conducted a 4-week, high-intensity interval training study designed to enhance endurance capabilities (i.e. the CP). They reported a significant 11 % and 10 % increase in CP and EP respectively, with there being no differences between the conventional and all-out asymptotic values (both in raw values and in Δ). However, while WEP and W' were correlated pre-training ($r = 0.82$, $P = 0.007$), they were not correlated post-training ($r = 0.63$, $P = 0.07$), with the $\Delta W'$ being significantly different to ΔWEP (-1.7 kJ and 0.6 kJ respectively; although the raw values of post-training W' and WEP were not statistically different). The predicting trials used pre- and post-training to derive the CP and W' were adjusted at both time points to provide similar durations of T_{lim} (although these data were not presented); therefore the estimates of CP and W' were not biased toward a higher W' and lower CP value simply by utilising longer T_{lim} trials in the 2-parameter linear model(s). As this is the only study to date examining the effect of high-intensity interval training on both the CP/EP and W' /WEP, it is difficult to determine whether the WEP parameter from the all-out test does indeed represent or faithfully estimate the W' , but it is apparent that the EP parameter of the all-out test does represent the CP (Vanhatalo et al., 2008a).

The remaining original 3-min all-out test publication highlights the necessity to set the 3-min all-out test resistance correctly (Vanhatalo et al., 2008b). Furthermore, this study adds to the evidence that the 3-min all-out test and the CP concept applied to all-out exercise are robust. Specifically, power output over the initial 30 s of the test was set at either 100, or 130 % P_{ramp} (from the incremental test) before the all-out portion of the test began for the remaining 2.5 min. Due to both 100 % and 130 % P_{ramp} being higher than the CP, WEP and EP were not different to WEP and EP obtained from the control 3-min all-out test (Control: EP = 254 ± 40 , WEP = 14.2 ± 3.7 ; 100 % trial: 249 ± 35 , 14.1 ± 3.7 ; 130 % trial: 245 ± 39 W, 15.9 ± 5.3 kJ). However, when the 3-min all-out test resistance was adjusted higher and lower than the control condition as to elicit end test cadences of either preferred cadence ± 10 (+10 rpm being the low and -10 rpm being the high resistance trials respectively), the P-D parameters from the 'adjusted' 3-min all-out tests changed notably (Vanhatalo et al., 2008b). While EP was unaffected with a higher resistance (-10 rpm: EP = 251 ± 38 W), the WEP parameter was artificially elevated (WEP = 16.2 ± 4.4 kJ) compared with control. In the low resistance (+10 rpm) condition both EP (244 ± 41 W) and WEP (12.9 ± 3.6 kJ) were artificially lowered compared with control. At the time, the authors speculated that this observation could be at least partly due to the hyperbolic relationship between crank force and crank velocity preventing participants spending as much time near 'optimal' cadences for maximal power production in the low resistance (+10 rpm) trial (Sargeant et al., 1981). Since then it has been observed that at high cadences (and thus duty cycles) fatigue develops faster compared with slower cadences (fewer duty cycles) during all-out cycling (Tomas et al., 2010).

Since the early work of Burnley et al. (2006) and Vanhatalo et al. (2007, 2008a), there has been significant interest in a single-visit test capable of ascertaining the parameters of the P-D relationship for severe-intensity exercise (Bergstrom et al., 2013a; Bergstrom et al., 2012; Bergstrom et al., 2013b; Bergstrom et al., 2013c, 2013d, 2013e, 2014; Clark, Murray, & Pettitt, 2013; Constantini et al., 2014; Francis, Quinn, Amann, & LaRoche, 2010). Much of this recent research has focussed on two predominant areas: 1) attempting to amend the 3-min all-out test set-up and protocol so it becomes a genuine single-visit test (rather than the original two-visit protocol), and, 2) how well the all-out CP and W'

parameters represent the upper boundary of the heavy-intensity domain and the fixed quantity of work which may be performed at exercise intensities $> CP$ respectively (Bergstrom et al., 2012; Bergstrom et al., 2013b; Bergstrom et al., 2013c, 2013d, 2013e, 2014; Clark et al., 2013; Francis et al., 2010).

Bergstrom et al. (2012) attempted to reduce the number of visits required for successful execution of a 3-min all-out test from two down to a single visit. Further, they also proposed that a less advanced and more affordable, friction braked cycle ergometer could be used for the 3-min all-out test. Based on pilot data, they proposed the use of 3.5 or 4.5 % of body mass as the flywheel resistance to maximally cycle against for three minutes. They compared the EP and WEP values from each of the 3.5 %, 4.5 % and original 3-min all-out test (albeit on an electronically braked, rather than electromagnetically-braked ergometer) to the CP and W' obtained from three exhaustive predictive trials. These authors reported that the original 3-min all-out test provided EP values significantly higher than conventionally derived CP (193 ± 54 vs. 178 ± 47 W respectively). Furthermore, the original 3-min all-out test EP value was significantly higher than EP from the 3.5 % 3-min test, but not different to the 4.5 % 3-min test. Surprisingly, despite having presented these results, the authors then conclude that the 4.5 % 3-min test may provide a single visit alternative to the original 3-min all-out test due to the similarities with the EP and WEP from the original 3-min all-out test (Bergstrom et al., 2012). This seems peculiar in light of the authors having the P-D parameters as determined using the gold-standard method. However, their further publications (discussed below) provide evidence that they may not be setting up the original 3-min test appropriately in order to derive all-out P-D parameters that corroborate with conventionally-derived P-D parameters. Another group have developed a more promising single-visit protocol with which to determine the P-D parameters using a 3-min all-out cycling test. Constantini et al. (2014) compared a 3-min all-out test (conducted as originally described, on originally described equipment) performed just 20 minutes after reaching exhaustion during a ramp-incremental test with a 3-min test conducted in isolation on a separate occasion. While the 3-min test performed in isolation was the 'criterion' measure, the agreement between the EP and WEP between the two tests was very similar to that reported originally (Burnley et al., 2006a; Vanhatalo et al., 2007). This protocol

thus becomes a viable single-visit method of determining the P-D relationship in humans (Constantini et al., 2014).

The original work on the 3-min all-out cycling test provides evidence that the test can accurately determine the boundary between heavy- and severe-intensity exercise (and thus the CP) within ± 15 W (Burnley et al., 2006a). The EP and WEP parameters of the all-out test provide valid estimates of their conventionally-derived CP and W' counterparts (Vanhatalo et al., 2007). The EP parameter of the test reliably tracks CP when the CP is altered via exercise training, but the WEP parameter tracks alterations in W' less well (Vanhatalo et al., 2008a). The 3-min all-out test parameters are unaffected by dietary interventions to increase alkalosis within the blood (Vanhatalo et al., 2010b), but are sensitive to detecting reductions in W'/WEP caused by prior sprint exercise and insufficient recovery (Skiba et al., 2012) for full W' reconstitution (Vanhatalo & Jones, 2009b). Importantly, the success of the 3-min all-out test to provide valid CP and W' estimates depends heavily on the resistance used during the all-out test; too small a resistance and both EP and WEP will be underestimated, too big a resistance and WEP will be overestimated, without a notable effect on the EP parameter (Vanhatalo et al., 2008b).

Table 2.2. Reliability of CP/EP and W'/WEP summary.

Reference	n	Modality	Methods	CP	W'	Notes
(Gaesser & Wilson, 1988)	11 M	C; conv.	5 trials 1/t model	CV 3% r = 0.96 SEE = 9 W MD = -7 W CI = -12 to -2 W	CV 8% r = 0.79 SEE = 1.97 kJ MD = 0.3 kJ CI = -0.94 to 1.54 kJ	T _{lim} target of 1 to 10 min. 10 P-D predicting trials performed prior to intervention.
(Jenkins & Quigley, 1992)	18 M	C; conv.	3 trials W/t model	r = 0.92	r = 0.97	Reliability data previously established within laboratory
(Nebelsick-Gullett et al., 1988)	25 F	C; conv.	3 trials	r = 0.94	r = 0.87	Trials performed on 1 day with ≥ 30 min rest separating. Re-test 1 week apart.
(Smith & Hill, 1993)	13 M	C; conv.	5 trials Non-linear	r = 0.92	r = 0.80	CP 5 & 6% higher in M & F respectively in second tests.
	13 F		P-t model	r = 0.90	r = 0.64	
(Burnley et al., 2011)	10 M	C; conv.	4 trials W/t model	CV 2% r = 0.99 SEE = 8 W MD = 1 W CI = -4 to 6 W	CV 16% r = 0.74 SEE = 3.44 kJ MD = -2.7 kJ CI = -4.81 to -0.59 kJ	Second set of trails performed subsequent to a 6-min heavy intensity 'priming' bout and 10 minutes of recovery – resulted in sig. mean increase in W'.
(Poole et al., 1990)	8 M	C; conv.	5 trials 1/t model	N/A	CV 8% r = 0.88 SEE = 2.19 kJ MD = -0.2 kJ CI = -1.59 to 1.19 kJ	Repeat tests performed ~ 8 weeks apart following a training intervention which elevated CP but not W'.
(Vanhatalo et al., 2007)	10	C; conv. & All-out	5 trials w/t model 3-min all-out	r = 0.99 SEE = 6 W MD = 0 W CI = -3 to 4 W	r = 0.84 SEE = 2.8 kJ MD = 1.00 kJ CI = -0.61 to 2.61 kJ	These reliability/validity statistics are comparing the all-out parameters to the 5-trial, W/t conv. CP and W'.
(Vanhatalo & Jones, 2009a)	7 M	C; All-out	3-min all-out	CV = 1% r = 0.99 SEE = 5 W MD = -3 W CI = -6 to 0 W	CV = 4% r = 0.92 SEE = 1.49 kJ MD = 0.16 CI = -0.85 to 1.17 kJ	All-out tests performed under placebo and creatine supplemented conditions.
(Vanhatalo et al., 2010b)	8 M	C; All-out	3-min all-out	CV 3%	CV 5%	NaHCO ₃ induced alkalosis prior to second 3-min all-out test – no effect on EP and WEP parameters.
(Burnley et al., 2006a)	9 M 2 F	C; All-out	3-min all-out	r = 0.99 SEE = 7 W or 3%	r = 0.97 SEE = 1.29 kJ or 9%	Reliability between repeated (identical) 3-min all-out tests (separate days, and subsequent to an additional, familiarisation trial).
(Vanhatalo & Jones, 2009b)	7 M	C; All-out	3-min all-out	CV 3 to 6%	Not reported	3-min tests performed 2 or 15 minutes after a 30 s maximal sprint.
(Johnson et al., 2011)	6 M 5 F	C; All-out	3-min all-out	CV 7% r = 0.93 SEE = 15 W	CV 21 % r = 0.87 SEE = 1.46 kJ	Reliability data is calculated from 'filtered' ergometer raw (6 Hz) data with a 2-pass Butterworth filter (5Hz cut-off)
(Constantini et al., 2014)	6 M 6 F	C; All-out	3-min all-out	CV 4% r = 0.99 SEE = 5 W	CV 12% r = 0.92 SEE = 1.81 kJ	Conventional 3-min test parameters compared against an identical test preceded by a ramp incremental test and 20 minutes recovery.
Combined published raw results from Gaesser & Wilson (1988), Burnley et al. (2011) (and for W', Poole et al. (1990)).	21 M (29 M for W')	C; conv.	4 to 5 trials 1/t & w/t models	CV 2% r = 0.99 SEE = 9 W MD = -3.1 W CI = -7 to 1 W	CV 10% r = 0.77 SEE = 2.60 kJ MD = -0.91 kJ CI = -2.13 to 0.31 kJ	Data here are an amalgamation of two or three published papers spanning over 20 years, where individual participant data is reported, enabling the calculation of CV, r and SEE.

M = male participants; **F** = female participants; **C** = cycling; **conv.** = conventionally-determined CP and W' ; **All-out** = all-out derived CP and W' ; **1/t** = power vs. inverse of time linear model (equation [2.2]); **W/t** = work vs. time linear model (equation [2.3]); **Non-linear P-t** = non-linear power vs. time model (equation [2.1]); **CV** = coefficient of variation; **r** = correlation coefficient; **SEE** = standard error of the estimate. **MD** = mean difference. **CI** = (95 %) confidence interval.

2.4. Tolerance to Exercise 'at' CP

Given the potential for day-to-day variation in physiological parameters (Wergel-Kolmert, Agehall, Rosenberg, & Wohlfart, 2001), the concept of exercising 'at' a physiological threshold is somewhat flawed. For example, the smallest variance with which CP can be identified is ~ 3 % (see Table 2.2 p49), the mathematical model used for its derivation can lead to a further ~ 24 % (see Table 2.1 p40) variation and submaximal $\dot{V}O_2$ can show day-to-day variability of ~ 6 % (Wergel-Kolmert et al., 2001). Therefore, if imposing the intensity of CP for a prolonged period, both the inaccuracy in the estimation in the parameter and the human variability should be taken into account. Indeed, when they are, and exercise intensity is set slightly below the estimated CP, heavy-intensity exercise responses are observed (Burnley et al., 2006a; Jones et al., 2008; Poole et al., 1988). Despite this, numerous researchers have attempted to examine the physiological response to exercise at the CP and, predictably, observed responses typical of severe-intensity exercise (Brickley et al., 2002; Jenkins & Quigley, 1990; McLellan & Cheung, 1992). In the investigations of Brickley et al (2002) and McLellan & Cheung (1992) there is no data presented on the span of exhaustion times witnessed during the predicting trials used for determination of the P-D relationship. However, certainly in the paper of Brickley et al. (2002), the highest power output used for one of the three exhaustive bouts was set at 120 % $\dot{V}O_{2max}$ power. Intentionally these authors set out to achieve exhaustion times ranging between 1 and 10 minutes, despite the available evidence suggesting the shortest predicting trial should approach 3 min (Bishop et al., 1998). In doing so, the highest power predicting trial is likely to have resulted in exhaustion in under 150 s (Busso, Gimenez, & Chatagnon, 2010) and therefore will have artificially 'raised' the estimate of the CP (Bishop et al., 1998). This would help explain why exercise at 'CP' resulted in non-

steady states in $\dot{V}O_2$, [Bla] and HR and termination of exercise in a mean time of 29:34 \pm 8:22 min:ss (Range 21:10 to 40:37; min:ss; (Brickley et al., 2002)).

McLellan & Cheung (1992) also reported short exercise tolerance (20.5 \pm 4.5 min) along with non-steady state measurements of $\dot{V}O_2$, V_E , [Bla], pH and Blood PCO_2 when exercising at CP. While on this occasion 5 exercise trials were used to characterise the P-D relationship, the authors again opted to include a predicting trial at 120 % of $\dot{V}O_{2max}$ intensity, which for at least some participants will likely have resulted in exhaustion in less than 150 s and an increased estimation of CP (Bishop et al., 1998; Busso et al., 2010). The exhaustion times of the P-D predicting trials were not published (McLellan & Cheung, 1992). However, Jenkins & Quigley (1990), while not reporting the exhaustion times overtly, do acknowledge that the mean time to exhaustion in the highest-power predicting trial was 81 s (mean exhaustion time for the lowest power trial being 719 s). Rather than speculate that this may have caused an inflated CP estimate, these authors instead suggest that CP overestimates the power sustainable for 30 min by 4.7 % (14 W) (Jenkins & Quigley, 1990). Jenkins & Quigley (1990) set out to determine the validity of the CP parameter as a measure of an exercise intensity that may be maintained for a very long time without fatigue. They then tasked their highly trained participants to cycle at CP for 30 min without providing a firm rationale for 30 min qualifying as “a very long time”. It is likely that had these authors utilised P-D predicting trials of appropriate duration, the estimates of CP would have been more appropriate and their participants would have been capable of exercising for “a very long time” (Bishop et al., 1998; Poole et al., 1988).

A similar phenomenon is observed in much of the more recent research using the all-out test to derive a CP estimate (Bergstrom et al., 2013c, 2013d; McClave, LeBlanc, & Hawkins, 2011). However, what many researchers including Bergstrom et al. (2013a; 2013b) and McClave et al. (2011) have failed to account for is the error in the determination of the CP (in all-out exercise TE of EP is between 6 and 15 W; Table 2.2 p49 (Johnson et al., 2011; Vanhatalo et al., 2007)). For example, in the average worst-case scenario, an EP could be calculated as 300 W yet the error could mean the ‘real’ EP is 285 W (or 315 W). If a constant-power exercise bout is set at the EP derived from the all-out test

(i.e. 300 W) then of course exercise will become intolerable due to being ~ 15 W into the severe-intensity domain. In the original all-out paper of Burnley et al. (2006), constant-power exercise bouts were indeed set at 15 W above and 15 W below the EP derived from the 3-min all-out cycling test and participants tasked with completing 30 minutes at these exercise intensities. 9 of the 11 participants completed 30 minutes of exercise at a power output of EP -15 W with 7 of these 9 participants reaching steady-state [Bla] and $\dot{V}O_2$ (at 85 % $\dot{V}O_{2peak}$). During constant-power exercise at EP +15 W none of the 11 participants tolerated 30 minutes (Mean T_{lim} 12.76 min, range: 1.83 to 23.95 min; (Burnley et al., 2006a)). Other 'successful' examples of witnessing the distinct response profiles of both heavy- and severe-intensity exercise are available (Burnley, Vanhatalo, & Jones, 2012; Jones et al., 2008) when constant-power/intensity exercise is performed just above and just below the CP (or critical torque). Combined, the evidence would suggest that when either or both the CP or EP are determined according to their respective guidelines, they do not significantly differ (Vanhatalo et al., 2007) from one another and indeed represent the boundary *between* heavy- and severe-intensity exercise (Burnley et al., 2006a; Poole et al., 1988; Vanhatalo et al., 2007).

It is perhaps too literal to expect the mathematically perfect definition of the exact boundary between sustainable and non-sustainable exercise intensities to be sensitive to a single watt. To identify this boundary to within 12 W (Burnley et al., 2006a), or better still 6 W (Vanhatalo et al., 2007), is practically very, very good reliability. It would be practically difficult for even a very finely tuned athlete to identify the difference between power outputs ~ 6 W apart. While these magnitudes of absolute power output may be indistinguishable through sensation in human participants, it is quite possible they play a notable role in affecting exercise tolerance.

2.5. Predicting Exercise Tolerance

The two-parameter CP model provides an accurate means of predicting exercise tolerance for a given constant-power output within the severe-intensity domain (Chidnok et al., 2013a; Housh, Housh, & Bauge, 1989; Vanhatalo et al.,

2007). At exercise intensities < CP exercise tolerance is less predictable and it would appear the fatigue process is influenced to a larger extent (than > CP) by central fatigue processes (Abbiss & Laursen, 2005; Amann, 2011; Burnley et al., 2012). However, once constant-power exercise is performed > CP, predicting exercise tolerance becomes more accurate (Ferguson et al., 2010; Hinckson & Hopkins, 2005; Vanhatalo et al., 2007). Mathematically, the W' is 'expended' only at power outputs above the power output corresponding to CP. It is logical to assume that a small proportion of W' may be expended in the initial seconds of any abrupt increase in power output due to the τ of the primary $\dot{V}O_2$ kinetics creating a delay between oxidative energy supply meeting instantaneous energy demand (Burnley & Jones, 2007; Morton, 2006). However, this potentially small utilisation of the W' in these circumstances would be impractical to quantify at < CP intensities due to W' being capable of replenishing (Skiba et al., 2012) and at > CP intensity, these 'utilisations' of W' form part of the full quantification of the parameter. Indeed when exercise is continued to exhaustion at power outputs within the severe-intensity domain, exhaustion will coincide with the full expenditure of the available W' and the attainment of $\dot{V}O_{2max}$ (Burnley & Jones, 2007; Jones et al., 2010; Poole et al., 1988).

Fukuba et al. (2003) provided clear evidence that the W' is utilised in an intensity dependent manner at intensities above the CP. Indeed, once the CP and W' parameters have been identified, the tolerable exercise time for a given power output can be accurately and reliably predicted (Ferguson et al., 2010; Ferguson et al., 2007; Murgatroyd et al., 2011; Vanhatalo et al., 2007). When the power output which should induce exhaustion at 6 min was calculated from the CP and W' derived from the power vs. $1/t$ linear model, mean T_{lim} was 365 ± 16 s (Murgatroyd et al., 2011). Furthermore, completing 6 minutes of severe-intensity exercise at a power calculated to cause exhaustion at 8 min, 2 min prior to an (or series of) exhaustive bout used to predict CP and W' , W' was reduced by ~ 35 %. At the completion of 6 minutes at the 8-min exhaustive power W' would be expected to be ~ 75 % reduced. Following 2 min of recovery, the available evidence suggests that PCr will have replenished to ~ 80 % of resting values (Bogdanis et al., 1995), so the reported ~ 35 % reduction

in W' seems roughly in line with these approximate calculations. Indeed, when the 3-min all-out test was conducted just 2 minutes following the completion of a 30 s maximal sprint, the WEP was $\sim 80\%$ of control WEP (Vanhatalo & Jones, 2009b). However, with the 3-min all-out test providing valid estimates of both the CP and W' in a single test, it should be possible to 'test' whether W' is expended at the rate(s) predicted by the mathematical model(s). For example, had Fergusson et al. (2007) conducted a 3-min test immediately at the completion of 6 minutes of cycling at the power eliciting exhaustion in 8 min, the WEP of the 3-min test would presumably have been reduced by $\sim 75\%$. Furthermore, the WEP should be unaffected, and thus fully 'in tact' if a 3-min all-out test were initiated from a moderate- or heavy-intensity exercise 'baseline'. While to date the 3-min test has only to be initiated from a 'zero' W' baseline there should be no reason that it cannot be initiated from different preceding exercise conditions. In fact, the utility of the all-out test in this sense could prove both useful and much quicker for answering further questions about the use of the W' during various stages during exercise tasks or environment conditions.

2.6. The Curvature Constant (W') of the P-D Relationship

It is well established that the W' represents a fixed amount of muscular work that may be performed at power outputs $> CP$ (Coats et al., 2003; Fukuba et al., 2003; Jones et al., 2010; Poole et al., 1988). However, the physiological underpinnings of the W' are still not well understood. Originally the W' was believed to comprise high-energy phosphates, a store of muscle glycogen linked to anaerobic glycolysis and myoglobin bound O_2 (Moritani et al., 1981; Poole et al., 1988). Indeed the evidence that expanding the intramuscular PCr store (Miura, Kino, Kajitani, Sato, & Fukuba, 1999; Smith, Stephens, Hall, Jackson, & Earnest, 1998) and depleting the muscle glycogen store (Miura, Sato, Whipp, & Fukuba, 2000) increases and decreases the W' respectively, supports this 'depletion' hypothesis. Certainly, thinking of the W' as a finite store of energy permitting the completion of a finite quantity of muscular work above CP is useful for conceptually grasping the CP concept and thus exercise tolerance within the severe-intensity domain. Yet, it is likely a too simplistic view of the physiological mechanisms determining the magnitude of the W' . For

example, the rapid splitting of PCr to Cr and P_i, while releasing ATP for muscle action, also creates an intra-muscular accumulation of P_i, which plays a detrimental role in a number of metabolic processes (discussed in section 2.7 Skeletal Muscle Fatigue) hindering continued, forceful muscle action (Allen & Trajanovska, 2012). Furthermore, anaerobic glycolysis will result in the accumulation of H⁺ and a reduction in the muscular pH (Allen, Lamb, & Westerblad, 2008b). In addition, sustained high-intensity exercise also leads to the accumulation of extracellular K⁺ and these factors combined alter the sarcoplasmic reticulum Ca²⁺ release and re-uptake, contributing to the loss of forceful muscle action (Allen, Lamb, & Westerblad, 2008a; Westerblad, Allen, & Lannergren, 2002). Therefore, an alternative 'accumulation' hypothesis has been proposed in order to explain the physiological underpinnings of the W' (Ferguson et al., 2010; Ferguson et al., 2007; Vanhatalo et al., 2010a).

Ferguson et al. (2010) investigated the kinetics of W' reconstitution in an attempt to better elucidate the mechanistic basis for this key parameter in determining severe-intensity exercise tolerance. To do so, Ferguson et al. (2010) had six male participants complete four constant-power exhaustive exercise bouts to initially characterise the P-D relationship (using the power vs. 1/t linear model). A power output that would result in exhaustion in 6 minutes was then calculated based on the CP and W' parameters. This power output was imposed and participants were required to cycle to exhaustion on each subsequent test occasion. Following completion of this bout, a recovery period of 2, 6 or 15 min was permitted prior to the completion of further exhaustive constant-power exercise bouts. Three exhaustive bouts were completed following each the 2, 6 and 15 min recovery periods (~ 14 visits per participant) to enable calculation of the CP and W' parameter alterations as a result of the three experimental recovery periods. As expected, based on their previous work (Ferguson et al., 2007), the CP parameter was unaffected by prior severe-intensity exercise or recovery duration (Control CP: 212 ± 34; 2 min CP: 213 ± 36; 6 min CP: 213 ± 34; 15 min CP: 213 ± 36 W). However, the W' parameter was significantly reduced compared with control W' following each recovery period and the W' parameter was also significantly different between each recovery duration (control W': 21.6 ± 5.2; 2 min W': 7.8 ± 1.4; 6 min W': 14.1 ± 3.7; 15 min W': 18.5 ± 4.6 kJ). The W' parameter had recovered to ~ 36, ~ 65

and ~ 85 % of the control W' value following 2, 6 and 15 min recoveries respectively. Compared to the two 'physiological' parameters also measured throughout each experimental trial ($\dot{V}O_2$ and [Bla]), the W' 'recharged' with kinetics somewhat faster than [Bla] but not as fast as $\dot{V}O_2$ (used as a proxy for PCr kinetics; See Fig. 5. p870 of Fergusson et al. (2010)), with neither physiological surrogate representing the W' replenishment kinetics (Ferguson et al., 2010). Importantly, this research provided the first evidence that contrary to the mathematical model of W' replenishment, the recovery kinetics were not linear, but rather curvilinear (Ferguson et al., 2010).

Further investigation into the reconstitution of the W' from dynamic cycling exercise has also suggested that the recharge kinetics are likely to be non-linear (Skiba et al., 2012). Furthermore, the exercise intensity below the CP appears to also play a key role in how rapidly the W' can replenish, with total rest permitting a faster reconstitution of W' ($W'\tau$; 377 ± 29 s; (Skiba et al., 2012)). Heavy-intensity 'recovery' exercise caused a slower $W'\tau$ (578 ± 105 s) and severe-intensity 'recovery' exercise caused such a slow $W'\tau$ that it became impractically large (7056 ± 11169 s), suggesting (in agreement with Coates et al. (2003)) that no W' replenishment can occur at power outputs greater than CP (Skiba et al., 2012). In an extension of this work, Skiba and colleagues attempted to validate a model enabling the calculation of instantaneous W' available (W'_{BAL}), using a variety of work-rest durations of intermittent exercise prior to an exhaustive exercise bout to the limit of tolerance (Skiba, Jackman, Clarke, Vanhatalo, & Jones, 2014). Skiba et al. (2014) unearthed some inaccuracies in their W'_{BAL} model when work and/or recovery durations were each ~ 20 s, observing short $W'\tau$ when work and rest bouts were 20 s each ($W'\tau = 212 \pm 114$) and longer $W'\tau$ when work and recovery durations were longer (60 s 'on', 30 s 'off'; $W'\tau = 403 \pm 164$). However, while the authors acknowledge their results warrant further investigation, their observation that more W' appeared to be 'available' when the $\dot{V}O_2$ at the start of the exhaustive bout was lowest, thus providing the greatest difference between 'starting' O_2 consumption and $\dot{V}O_{2peak}$, provides compelling evidence toward the putative importance of $\dot{V}O_2$ kinetics in the physiological underpinning of the W' parameter.

In a 2007 review, Burnley & Jones (2007) outlined how $\dot{V}O_2$ kinetics can help explain changes in the more 'traditional' physiological constructs (e.g. LT, $\dot{V}O_{2max}$ & economy/efficiency), focusing much of the review on the importance of phase II τ and the $\dot{V}O_2$ slow component. They clearly presented how the $\dot{V}O_2$ kinetics behave in response to different intensities of severe-intensity exercise. At power outputs just above the CP, the $\dot{V}O_2$ slow component rises slowly over time, eventually reaching $\dot{V}O_{2max}$ and coinciding with the expenditure of the W' and therefore exhaustion ensues. When power output is much higher than CP, the slow component rises more steeply toward $\dot{V}O_{2max}$ with similar consequences occurring albeit somewhat sooner. Importantly, the magnitude of the power output dictates the primary amplitude of the $\dot{V}O_2$ response, and given (provided $>$ CP exercise is continued) the slow component will reach $\dot{V}O_{2max}$ at exhaustion, the largest slow component amplitudes are observed at power outputs only just above the CP (Burnley & Jones, 2007). As the $\dot{V}O_2$ slow component will always project toward $\dot{V}O_{2max}$ at power outputs above the CP, any intervention that causes an increase in CP also increases the range of power outputs residing in the heavy-intensity domain. Assuming the CP was the only parameter to change, this would also result in a 'smaller' severe-intensity domain; consequently, the range or span of $\dot{V}O_2$ slow component amplitudes would theoretically be reduced, and ostensibly so too would the size of the W' . Conversely, if the $\dot{V}O_{2max}$ were to be increased without a change in CP, the 'size' of the severe-intensity domain would be increased, enabling a larger $\dot{V}O_2$ slow component amplitude and presumably a larger W' (Burnley & Jones, 2007). As such the $\dot{V}O_2$ slow component and the W' parameter of the P-D relationship may possess some form of causal link.

These predictions by Burnley and Jones (2007) were based on limited evidence but sound physiological theory and underpinnings. Since these predictions, numerous publications provide additional and in some cases, strong evidence that a link between the $\dot{V}O_2$ slow component and the W' exists. Vanhatalo et al. (2010) found that a hyperoxic inspirit (70 % O_2) significantly increased the phase II (PCr) τ and thus decreased the overall 'speed' of the PCr kinetics (Mean response time; MRT) compared with normoxia (normoxia MRT: 59 ± 20 ; hyperoxia MRT: 116 ± 46 s, $P < 0.05$). The amplitudes of the PCr primary

response and slow component did not differ between conditions. Despite this, a reduced ($\sim -19\%$) W' was reported. Based on $\dot{V}O_2$ kinetics responses, the consistency of the slow component amplitude across normoxic and hyperoxic conditions would be expected to result in no change in the W' if the two ($\dot{V}O_2$ slow component and W') were causally linked (Burnley & Jones, 2007). However, the kinetics examined by Vanhatalo et al. (2010) were limited to muscle metabolites, PCr, P_i , H^+ and did not include any $\dot{V}O_2$ measurement. It was suggested by the authors that in the hyperoxic condition, the kinetics of $\dot{V}O_2$ and PCr may have become uncoupled (Vanhatalo et al., 2010a), and thus the link between the $\dot{V}O_2$ kinetics and the P-D relationship parameters still warranted further examination.

Murgatroyd et al. (2011) set out to determine the link between the $\dot{V}O_2$ slow component and the parameters of the P-D relationship with the hypothesis that the CP would be inversely related to the Phase II $\dot{V}O_2$ τ (that being participants exhibiting a high CP would also possess a short primary τ) and that W' would positively correlate with the $\dot{V}O_2$ slow component amplitude. Having determined the CP and W' via the linear power vs. $1/t$ model and at least four exhaustive trials the power output that would elicit exhaustion at 6 min was calculated and subsequently used to 'normalise' severe-intensity exercise tolerance across all fifteen participants for the examination of the $\dot{V}O_2$ kinetics. Following the completion of five repeated exhaustive bouts at the power output causing exhaustion at 6 min (mean T_{lim} : 365 ± 16 s; CV: 4 % between repeated tests) a significant negative correlation between CP and Phase II τ ($r = -0.95$, $P < 0.05$) emerged, along with a significant positive correlation between W' and $\dot{V}O_2$ slow component amplitude ($r = 0.84$, $P < 0.05$; (Murgatroyd et al., 2011)). This was the first study to firmly link the P-D parameters with those of the $\dot{V}O_2$ kinetics in explaining severe-intensity exercise tolerance. Other publications provide further support for this link (Dekerle et al., 2012; Ferguson et al., 2010; Ferguson et al., 2007; Jenkins & Quigley, 1992; Poole et al., 1990) but were unable to formally draw any association. Observing that the $\dot{V}O_2$ kinetics have the potential to alter the parameters of the P-D relationship opens the door to further investigations where the $\dot{V}O_2$ kinetics are purposefully manipulated to induce expected alteration in one or both of the CP and W' .

2.6.1. Putative underpinnings of the W' parameter

1) $\dot{V}O_2$ Kinetics

Since the work of Gerbino et al. (1996), presenting data to suggest that the $\dot{V}O_2$ kinetics are 'speeded' following a prior bout of heavy-intensity exercise, there has been much interest in 'priming' bouts and subsequently enhanced severe-intensity exercise tolerance (Bailey et al., 2009a; Burnley et al., 2002; Gerbino, Ward, & Whipp, 1996). It has since become accepted that the phase II τ of the $\dot{V}O_2$ kinetics is not actually 'speeded' (in young healthy individuals) with prior heavy or severe-intensity 'priming' exercise but rather the phase II (primary) amplitude is typically increased and the $\dot{V}O_2$ slow component concomitantly reduced resulting in a 'speeding' of the overall $\dot{V}O_2$ kinetics (MRT; (Bailey et al., 2009a; Burnley et al., 2002)). Burnley et al. (2011) specifically investigated the effects of heavy- and severe-intensity 'priming' exercise on the P-D relationship parameters. Each priming bout preceded (by 10 min) a severe-intensity predicting trial to the limit of tolerance. Heavy-intensity priming (performed at $\sim 25\% \Delta$; 50 % of the difference between GET and CP) resulted in (i) an increased primary $\dot{V}O_2$ amplitude, (ii) a reduced $\dot{V}O_2$ slow component trajectory, (iii) a reduced $\dot{V}O_2$ slow component amplitude, (iv) $\sim 19\%$ increase in exercise tolerance, and (v) $\sim 17\%$ increase in W' compared with the non-priming control condition; CP was unchanged, as hypothesised. Whereas, severe-intensity priming exhibited all the same responses as heavy priming on the $\dot{V}O_2$ kinetics, no effects were observed on the CP or the W' parameters (Burnley et al., 2011). The authors acknowledged that the lack of effect of severe-intensity priming on the W' is likely due to the duration of the recovery period (10 min) between the end of the priming bout and the beginning of the exhaustive exercise bouts. Previously, the same normalised power output has been used prior to exhaustive bouts but with a shorter, 2 min, intervening recovery period (Ferguson et al., 2007). When a 2 min recovery was given, the W' was reduced by $\sim 34\%$ compared to control. The time course of W' reconstitution appears to have τ of ~ 336 (full replenishment in ~ 22.5 min; (Skiba et al., 2012)), thus following a 10 min recovery period having completed an exercise bout which should have expended $\sim 75\%$ of W' (6 min of exercise at a power output sustainable for 8 min; $6/8 = 0.75$), it is unlikely that W' would have fully reconstituted. Therefore, as Burnley et al. (2011) note, it may be that the severe

priming bout also resulted in an elevation in W' but perhaps the beneficial effect of the enhanced $\dot{V}O_2$ kinetics response was 'offset' by the markedly reduced W' due to the prior severe bout.

Whilst the Burnley et al. (2011) paper was not the first to examine the effects of $\dot{V}O_2$ kinetics priming on the P-D parameters, it is the first to strictly position priming bouts into either the heavy- or severe-intensity exercise domains. Previously, Miura et al. (2009) had participants complete P-D predicting trials preceded by 6 min of cycling at a power output equivalent to 50 % Δ and a 6-min recovery period. No change in W' was reported compared with control W' but a significant increase in CP was determined following the priming bout (Control CP: 169 ± 31 ; Primed CP: 177 ± 34 W). However, as noted by Burnley et al (2011), the CP parameter typically occurs ~ 50 % Δ , therefore, it is plausible that for some of the eight participants the priming was performed within the heavy-intensity domain, while for others the priming bout was of severe-intensity. The study of Burnley et al. (2011) likely provides more comprehensive detail as to the effects of either heavy- or severe-intensity priming exercise on the P-D parameters. In both experiments however, due to the performance-enhancing effects of priming on exercise tolerance, issues surrounding the duration of exhaustive predicting trials arise (see section 2.2.7).

2) Muscle Cross Sectional Area

Using either, or indeed the combination of the 'depletion' or 'accumulation' hypotheses for explaining the physiological determinants of the W' , it stands to reason that a bigger muscle or specifically a muscle with greater volume may exhibit a larger W' ; i.e. a muscle with a larger PCr and glycogen store or greater capacity to accumulate P_i and H^+ . Indeed, an association between thigh cross sectional area and W' ($r = 0.59$) was reported by Miura et al. (2002). The authors acknowledge that cross section alone is too simplistic to explain the magnitude of the W' as the muscle fibre composition will have a distinct effect on the glycogen, PCr, ADP and ATP content of the muscle in question (Nevill & Greenhaff, 1999), all of which should affect the measurable W' (Miura et al., 2000). While Miura et al. (2002) indeed observed a positive moderate correlation between mid-thigh circumference and W' , this was a cross-sectional snap shot of 17 healthy males. Had they have introduced a strength training

intervention designed to increase the cross sectional area of the thigh and re-assessed the P-D relationship, again witnessing a strong correlation between cross-sectional area and W' combined with larger W' values, this would go some way to validating the potential relationship between muscle size/volume and the magnitude of the W' . Based on either the 'depletion' or 'accumulation' hypothesis, it stands to reason that a larger volume of muscle mass pertains to either (or both) a larger potential glycogen store or a greater PCr store, either of which may theoretically permit a greater amount of 'anaerobic' work to be completed.

3) Muscle Creatine Content

In testing whether increasing muscle PCr content had an appreciable effect on the W' parameter, a number of experiments have attempted to provide the answer through the use of creatine monohydrate supplementation (Miura et al., 1999; Smith et al., 1998; Vanhatalo & Jones, 2009a). In very similar studies, both Smith et al. (1998) and later, Miura et al. (1999) report that acute (5-day) supplementation with 20g of creatine per day resulted in no change in the CP parameter but a significant increase in the W' of the P-D relationship (Miura et al: Placebo W' : 10.9 ± 2.7 ; creatine W' : 13.7 ± 3.0 kJ, $P < 0.05$; Smith et al: placebo baseline W' : 218 ± 39 , placebo experimental W' : 200 ± 47 J/kg; creatine baseline: 212 ± 58 , creatine experimental: 234 ± 48 J/kg, $P < 0.01$). Although slightly different experimental designs were employed by the two studies; both reported substantial increases in T_{lim} during the highest constant-power predicting trials. This elevation in T_{lim} was attributed to a greater 'anaerobic' energy store contributing to energy supply during these more energy demanding exhaustive trials. As detailed above (section 2.2.7. *Duration of Predicting Trials*), this lengthening of T_{lim} is likely to result in an increase in the W' parameter estimate. However, while Smith et al. (1998) did not measure $\dot{V}O_2$, Miura et al. (1999) reported no increase in the $\dot{V}O_{2max}$ in combination with the reported elevation in W' . This is somewhat at odds with the expected response of the W' , $\dot{V}O_2$ kinetics, the CP and the $\dot{V}O_{2max}$ (effectively the 'size' of the severe domain – see 2.6.1. '1) $\dot{V}O_2$ kinetics' for further detail). More recently the 3-min all-out test has been used to re-assess any changes in the P-D relationship following an identical creatine supplementation period (Vanhatalo & Jones, 2009a). The all-out P-D parameters, EP & WEP, were unaffected by

creatine supplementation, as were total work done, the power profile of all-out test and $\dot{V}O_{2max}$. While the sensitivity of the 3-min all-out test WEP parameter is unlikely to be able to detect relatively small changes (~ 5 to 10 %) in the W' due to the CV of the WEP (~ 8 %; (Vanhatalo, 2008)), neither is the conventional CP analysis due to the errors in the mathematical modelling of various exercise trials each also exhibiting error in T_{lim} (Hill, 1993; Hinckson & Hopkins, 2005). A potential advantage of the 3-min all-out test is that the result is a stand alone, not subject to additional 'error' via a modelling process (Vanhatalo & Jones, 2009a).

4) Muscle Glycogen Content

Another predicted constituent of the W' is that of muscle glycogen (Hill, 1993; Moritani et al., 1981; Poole et al., 1988). Either involved as a substrate fuelling anaerobic glycolysis, or implicated via the resultant H^+ ion from anaerobic glycolysis, glycogen stored within the muscle fibre has the potential to affect high-intensity exercise tolerance (Maughan & Poole, 1981). Maughan & Poole (1981) manipulated muscle glycogen content in both directions (depletion and supercompensation) via a dietary intervention over a number of days (Bergstrom, Hermansen, Hultman, & Saltin, 1967) preceding an exercise tolerance test at 105 % $\dot{V}O_{2max}$ intensity. The T_{lim} under normal dietary conditions was 4.87 ± 1.07 min, suggesting firmly that the intensity of the exhaustive bout resided within the severe-intensity domain (Burnley & Jones, 2007; Hill, 1993; Poole et al., 1988). When a low (2.6 ± 1.9 % of total energy intake from CHO) carbohydrate diet preceded the exhaustive bout, T_{lim} was reduced by ~ 34 % (3.32 ± 0.93 min, $P < 0.005$). When a high CHO (84.2 ± 5.6 % total energy from CHO) diet was consumed prior to the exhaustive bout, T_{lim} was significantly increased by ~ 35 % compared to 'normal' dietary conditions (6.65 ± 1.39 min, $P < 0.05$). Although the magnitude of performance decrement and improvement is not as large, these results (Maughan & Poole, 1981) emulated results of Bergstrom et al. (1967) who, following a similar dietary manipulation and exhaustive exercise task at 75 % $\dot{V}O_{2max}$ (likely to be at the upper end of the heavy-intensity domain), reported a 50 % reduction and a 46 % increase in T_{lim} following the low and high CHO diets respectively, compared to the normal diet condition (T_{lim} of 114 min). Since then, it has been determined that muscle glycogen use is proportional to exercise intensity (van Loon,

Greenhaff, Constantin-Teodosiu, Saris, & Wagenmakers, 2001). As such, it would be intuitive to have expected exercise tolerance at 105 % $\dot{V}O_{2max}$ to have been reduced/expanded to a greater extent than at 75 % $\dot{V}O_{2max}$, due to greater muscle glycogen utilisation at higher intensity. However, given that the T_{lim} at 75 % $\dot{V}O_{2max}$ was ~ 114 min, and thus likely heavy-intensity (Burnley & Jones, 2007), different fatigue processes are likely implicated in determining T_{lim} compared to exercise > CP (Abbiss & Laursen, 2005; Amann, 2011). Either way, the results of Maughan & Poole (1981) provide some quite compelling data suggestive of muscle glycogen's key role in exercise tolerance within the severe domain, which warrants further investigation.

Subsequently, there has been only a single publication explicitly investigating the effects of glycogen depletion on the tolerance to severe-intensity exercise and the parameters of the P-D relationship (Miura et al., 2000). Miura et al. (2000) replicated the glycogen depletion protocol of Heigenhauser et al. (1983) with seven male participants which they expected to result in ~ 50 % reduction in muscle glycogen content. This required the completion of 75 min submaximal cycling at 60 % $\dot{V}O_{2max}$, a 5 min rest and (a mean completion of eight) repeated 1 min cycle bouts at 115 % $\dot{V}O_{2max}$, interspersed with 1 min of recovery, continued to exhaustion. After an overnight fast, participants performed (on separate occasions) four severe-intensity exercise trials to the limit of tolerance for determination of CP and W' (linear power vs. 1/t model). The same exhaustive trials were also completed without prior glycogen depletion exercise. All exhaustive bouts were separated by at least 1 week (~ 11+ visit protocol spanning at least 9 weeks). They reported a non-significant ~ 6 W (3 %) reduction in CP and a significant ~ 2.5 kJ (20 %) reduction in W' as a consequence of the muscle glycogen depletion (Miura et al., 2000). Although the authors do not present the T_{lim} data, studying the 'representative' participant's data clearly shows T_{lim} some ~ 30 s shorter in the glycogen depleted state for the shortest two predicting trials when compared with the normal glycogen condition (Figure 1. p 136: (Miura et al., 2000)). This corresponds to a decrease in T_{lim} of ~ 25 %; similar to that reported by Maughan & Poole (1981). As has been discussed above, in doing so, the W' estimate is likely to be underestimated, particularly due to the total duration of the shortest predicting trial becoming < 100 s. Given these methodological

shortcomings it becomes difficult to determine whether or not glycogen depletion has a detectable effect on the W' parameter. Yet, the evidence suggesting severe-intensity exercise tolerance, particularly of shorter duration, becomes compromised when muscle glycogen is reduced appears reasonably strong. When this is considered in combination with the additional evidence that lower intensity (that around or just below the CP) exercise tolerance also becomes limited when muscle glycogen is reduced (Bergstrom et al., 1967), the contribution of muscle glycogen to both the W' and the CP parameter poses an interesting question. Sustained heavy-intensity exercise relies up on (van Loon et al., 2001) and becomes limited by (Bergstrom et al., 1967) muscle glycogen. Therefore, in addition to the W' , muscle glycogen could play a determining role in the CP.

2.6.2. Summary

In comparison to the CP, the constituents of W' are relatively poorly understood at present, but a number of viable and attractive putative explanations exist. The quest to determine the physiological underpinnings of the W' is justified; for a given CP, the W' alone dictates muscular performance capability within the severe-intensity domain. It is within this domain the majority of linear, endurance sporting events are contested. Events lasting over ~ 2 min and less than ~ 45 min will likely encapsulate the severe-intensity domain (Burnley & Jones, 2007). Within this spectrum of exercise duration (~ 2 to 45 min), the W' plays an increasing role in performance capability as the event duration reduces. i.e. the W' effectively plays a larger relative contribution to the female 3 km individual pursuit (~ 3 min 30 s) than it does to the 10 mile road time trial ($\sim 19 - 21$ min). As the event duration increases, the sustainable rate of ATP provision (the CP) plays a larger and larger role in performance capability. However, the majority of linear, endurance Olympic medals are raced for over duration between ~ 2 min (800 m track and field) and ~ 6 min 30 s (single sculls 2 km rowing). Therefore, the W' is likely to become a strong correlate with successful performance over these types of sporting events. Thus, determining the physiological explanation(s) for the W' would provide the knowledge necessary to specifically manipulate certain aspects of this physiology to help

induce increases in this parameter, and thus exercise tolerance/performance over relatively short-duration endurance events.

2.7. Skeletal Muscle Fatigue

Skeletal muscle fatigue remains one of the most researched areas in exercise physiology and biochemistry. Fatigue is studied from a range of depths from the cellular level, right up to the external mechanical fatigue observed in whole-body power output (e.g. the CP concept). However, a definitive understanding/explanation of muscle/whole body fatigue remains elusive. Numerous excellent review papers detail our current best understanding of peripheral muscle fatigue at the cellular level (Allen et al., 2008b; Allen & Trajanovska, 2012; Debold, 2012b; Fitts, 1994; Westerblad & Allen, 2002; Westerblad et al., 2002). A brief overview will be provided below

Fatigue can be defined as the progressive decline in muscle force generating capacity, which is reversible with a period of rest (Allen et al., 2008b). The fatigue of exercising musculature can be attributed to any part of the neuromuscular action; initiating in the motor cortex within the brain, the action potential (AP) travels down the motor neurons of the spinal cord and to the neuromuscular junction of the exercising muscle where the signal for muscle contraction must be carried out by the peripheral, skeletal muscle (Allen et al., 2008b). As was defined by Allen et al. (2008), fatigue processes within the spinal cord and brain are classified as 'central fatigue', whereas processes beyond the peripheral nerve, (neuromuscular junction and muscle) are considered 'peripheral' (Gandevia, 2001).

2.7.1 Muscle action

Action potentials are conducted along the sarcolemma with extracellular Na^+ entering the cytoplasm and concomitantly, K^+ leaving the cytoplasm into the extracellular space. This AP is passed along the transverse tubules (t-tubules), which are proximal to the sarcoplasmic reticulum (SR) causing a change in membrane voltage on the SR. Voltage-sensitive membrane proteins are activated enabling Ca^{2+} to leave the SR and enter the cytosol surrounding the

myofibril. This myoplasmic free calcium ($[Ca^{2+}]_i$) is free to bind to troponin C, causing: (i) movement of tropomyosin; (ii) opening of the myosin binding sites on the actin filaments and; (iii) enabling the crossbridge cycle to begin, with muscle force generation being the subsequent result (Ashley, Mulligan, & Lea, 1991). When the muscle is no longer activated/innovated, $[Ca^{2+}]_i$ is actively pumped back into the SR via ATP-driven Ca^{2+} pumps on the SR membrane. Due to the vast muscular network around the body, the t-tubular network contains roughly 50 % of the body's Na^+ - K^+ pumps, which therefore require considerable ATP to sustain muscle excitation and relaxation; this ATP can be synthesised locally to the junction between the t-tubules and the SR (triad junction) and is used preferentially to ATP synthesised from within the cytoplasm (Allen et al., 2008b). During initial or sustained high-intensity muscle action, muscle ATP consumption will (initially at least) exceed ATP production. However, any ATP 'deficit' is prevented through the rapid creatine kinase and adenylate kinase reactions, catalysing the conversion of PCr and 2 ADP (respectively) into ATP. In doing so, a typical alteration in metabolites occurs within the muscle; [PCr] will fall with accompanying increases in [Cr] and [P_i] (Allen et al., 2008b; Cady, Jones, Lynn, & Newham, 1989).

2.7.2. Extracellular K^+

With each AP $\sim 2 \mu M$ and $10 \mu M$ K^+ leaves slow and fast muscle cells respectively. With repeated activation of muscle, net K^+ efflux occurs leading to increased extracellular K^+ concentration ($[K^+]_{ex}$). In well-perfused muscle working at high intensity, $[K^+]_{ex}$ can become more than double the resting concentration (increasing from ~ 4 mM to ~ 10 mM). This elevation in extracellular K^+ has clear implications for conductance of the AP and subsequent muscle activation. However, in exercising humans, this reduced excitability appears not to be the cause of reduced force output from the muscle (Allen et al., 2008b; Sandiford et al., 2005). Numerous compensatory events unfold, such as a reduction in Na^+ channel activity and increased t-tubules chloride (Cl^-) conductance both helping to repolarise the sarcolemma and ensure APs can continue (Allen et al., 2008b). With the muscle continuing to be innovated by the nervous system, perturbation within the metabolic milieu within and around the muscle also continue, particularly in the fast twitch fibres. PCr,

ADP, IMP and intracellular free magnesium concentration ($[Mg^{2+}]_i$) all increase in response to a rapidly reducing cytoplasmic [ATP]. The increased [IMP] actually causes a slight increase in Ca^{2+} sensitivity of the muscle while the elevation in $[Mg^{2+}]$ has the opposite effect on Ca^{2+} sensitivity without affecting either the maximum force or shortening velocity of the myofibril (Allen et al., 2008b; Blazev & Lamb, 1999; Dutka & Lamb, 2004). These subtle changes in contractile properties of the fast twitch fibres are likely to act in addition to the Ca^{2+} altering effects of P_i and H^+ (Allen et al., 2008b). The specific mechanisms and interplay between these ionic perturbations is complex but current understanding suggests that the triad junction between t-tubules and SR may hold a key role in sensing the depletion in cellular [ATP] and subsequently limit the release of Ca^{2+} . Consequently, with lower $[Ca^{2+}]_i$ fewer cross bridges are formed, less ATP consumed and also less Ca^{2+} is resequenced by the SR; the net result obviously being a reduced contractile force in the muscle and thus 'fatigue' (Allen et al., 2008b).

2.7.3 Inorganic Phosphate (P_i)

The increase observed in intracellular $[P_i]$ has been implicated in the reduction in force observed with high-intensity contractions. P_i may act at the cross-bridge between the actin and myosin head, inhibiting a high-force state in fast-twitch muscle fibres; but at physiological temperatures, this inhibition may account for ~ 10 % of the reduction in maximum force (Allen et al., 2008b). Rather, P_i is strongly linked to reduced myofibrillar Ca^{2+} sensitivity (Medved, Brown, Bjorksten, & McKenna, 2004) and a high $[P_i]$ can inhibit SR Ca^{2+} pumping out of the cytosol, leading to an increase in tetanic $[Ca^{2+}]_i$ (Allen et al., 2008b; Dawson, Gadian, & Wilkie, 1980). Furthermore, during fatiguing contraction where P_i accumulates in the cytosol, P_i ions can enter the SR and form a Ca^{2+} - P_i precipitate, further reducing the SR $[Ca^{2+}]$ and thus leading to the decrease in SR Ca^{2+} release (Allen et al., 2008b; Fryer, Owen, Lamb, & Stephenson, 1995). With calcium being a key ion in skeletal muscle contraction and relaxation, it seems reasonable that P_i may well be a fundamental inhibitory metabolite for sustained high-intensity contraction due to the multifaceted consequences of P_i on Ca^{2+} exchange and availability. Indeed, P_i is observed to rise inexorably with

time in vivo when exercise is sustained with the severe-intensity domain until exhaustion (Jones et al., 2008).

2.7.2. pH/H⁺

In addition to Pi, pH is observed to decrease (H⁺ increase) inexorably with sustained severe-intensity exercise (Jones et al., 2008; Vanhatalo et al., 2010a). Lactic acid (from which H⁺ splits leaving H⁺ and lactate) has been linked with muscle fatigue (Fitts, 1994) due to its appearance alongside 'fatigue' during high-intensity exercise. Lactate is essential to enable glycolysis to take place in the absence of oxygen; converting pyruvate to lactate. Rather than lactate *per se*, it would be the H⁺ ion (which readily splits from lactic acid) that has implications for continued muscle action due to the rise in local acidity (~0.5 reduction in pH (Sahlin, Harris, Nylinde, & Hultman, 1976)). The lowering of pH was thought to reduce muscle force by blunting the release of SR Ca²⁺ by specifically altering the activity of calcium release channels. However, this has since been found not to be the case; in fact, lower pH within the muscle cell can actually benefit the [Ca²⁺]_i, leading to a maintained or increased force output of the exercising muscle (Allen et al., 2008b; Westerblad & Allen, 1993). The lower pH within the muscle was also believed to reduce the activity of glycolytic enzymes (e.g. pyruvate dehydrogenase (PDH)) and while this is strictly true, the enzymes still maintain substantial activity despite a lower pH (Allen et al., 2008b). Lactate may also play an advantageous role due to its re-conversion into glucose (Cori cycle) to then re-feed glycolysis. Taken together neither lactate or lactic acid, nor a reduced pH appear to play any major role in skeletal muscle fatigue (Allen et al., 2008b). However, many more ions are involved, not only in the contractile machinery, but also the excitation of the muscle, with each potentially playing a co-contributory role in the muscle fatigue process.

A combination of interactions between numerous ions are implicated in both muscle action and the fatigue process. There is a developing bank of evidence to suggest that the decline in muscle force may occur on a per-contraction basis; that being, at higher duty cycles, the reduction in force output of the muscle declines more steeply compared with lower duty cycles (Broxterman et al., 2014; Tomas et al., 2010). This per-contraction fatigue observed at the

external mechanical level for 'all-out' type exercise is also measurable at the mouth during constant-power exhaustive exercise at high pedal speeds by way of a reduction in exercise efficiency (Barker, Poole, Noble, & Barstow, 2006; McDaniel, Durstine, Hand, & Martin, 2002). The result is a reduction in CP at high, compared to low pedal rates (Barker et al., 2006; Carnevale & Gaesser, 1991; McNaughton & Thomas, 1996). One of the more practical interventions available with which to alter muscle fatigue at a given absolute power output is exercise training, which can have profound effects on dynamic muscle performance capabilities and ostensibly, the P-D relationship.

2.8. Influencing the Magnitude of P-D Parameters with Training

In addition to high pedal rates affecting the CP (Carnevale & Gaesser, 1991), it has been demonstrated that CP is also reduced in response to acute hypoxia (Moritani et al., 1981) or ischemia (Scherrer, Samson, & Paleologue, 1954) and enhanced in response to hyperoxia (Vanhatalo et al., 2010a). Less direct evidence suggests that CP would likely be compromised following blood donation (450 ml loss of whole blood) due to a consistently compromised $\dot{V}O_{2peak}$ and severe-intensity exercise tolerance (Burnley et al., 2006b; Hill, Vingren, & Burdette, 2013). Furthermore, there is a developing body of evidence outlining the expected alteration in both the CP and W' in response to exercise training.

One of the earliest training studies (Gaesser & Wilson, 1988) exploring the response of the CP and W' to training, compared the effects of either continuous (40 min at 50 % $\dot{V}O_{2max}$) or interval (10 x 2 min bouts at 100 % $\dot{V}O_{2max}$) training performed 3 days per week for 6 weeks. Interval training and continuous training resulted in 15 % and 13 % increases in CP respectively while the W' parameter was statistically unaffected (but tended to decrease very slightly by ~ 1 kJ in both training groups; -6 % and -7 % for continuous and interval groups respectively). $\dot{V}O_{2max}$ increased only in the interval training group by ~ 5 %. Later, Poole et al. (1990) employed a similar, 7-week interval-training regime requiring the completion of 10, 2 min intervals at 105 % $\dot{V}O_{2max}$ three days per week. They also reported a significant 10 % increase in CP, yet no

change in W' (Pre: 14.6 ± 1.6 ; Post: 14.8 ± 1.5 kJ) and a 15 % significant increase in $\dot{V}O_{2max}$ in their eight healthy male participants (Poole et al., 1990).

In the early 90s, Jenkins & Quigley published two training studies where CP and W' were assessed in response to endurance training (Jenkins & Quigley, 1992) and high-intensity interval training (Jenkins & Quigley, 1993). In response to 8 weeks of endurance training (30 to 40 minutes at an intensity tolerable for ~ 40 minutes, three times per week), the 12 untrained male participants increased CP by 30 %. The control group ($n = 6$) showed a non-significant increase in CP of 5 %. $\dot{V}O_{2max}$ increased by 8 % in the training group with no change (1.5 %) in the control group. The change in CP and $\dot{V}O_{2max}$ of the training group were not significantly correlated ($r = 0.32$). Although no statistically significant changes were observed in the W' parameter, the training group exhibited a 26 % reduction and the control group a 23 % reduction. In an additional 'test' Jenkins & Quigley (1992) had their participants complete 40 minutes of exercise at the intensity of the calculated CP both pre- and post-training. On both occasions, the power output had to be adjusted down in most participants to enable the 40-minute duration to be tolerated. While the change in average power sustained for 40 minutes increased by 28 % over the training period in the training group, this 40 min average power was 5.4 and 5.7 % lower than the calculated CP pre- and post-training respectively ($n = 18$). It is interesting to note that the authors do report the mean duration of the lowest intensity exhaustive predicting trial for the P-D relationship, which was a little over 5.5 min (337 ± 173 s). Thus, the relatively small 'range' of durations over which the P-D relationship was characterised could have contributed to the apparent systematic 'overestimation' of CP by these authors.

Given the striking response of the CP to heavy-intensity continuous training, these authors next characterised the response of the P-D relationship to 'high-intensity training' (Jenkins & Quigley, 1993). Whereas the previous research to this point had used 2-min 'high-intensity' bouts in their training stimulus for the P-D parameters (Gaesser & Wilson, 1988; Poole et al., 1990), Jenkins & Quigley opted for a 60 s work period. The training again consisted of 3 sessions per week for 8 weeks. The training sessions consisted of 5 repetitions of 60 s maximal (all-out) efforts separated by 5 minutes of passive rest. The training

period resulted in a non-significant 3 % and 2 % increase in CP in the training and control groups respectively. $\dot{V}O_{2max}$ increased only in the training group, by 10 %. Interestingly, the training group experienced a significant 49 % increase in the W' , while the control group showed no change (6 %). There was also a significant 16 % increase in work completed during a training session as a result of the 8-week training intervention with the increase in W' and work completed in a training session being significantly correlated ($r = 0.92$, $P < 0.01$, $n = 15$). The authors conclude that this repeated all-out “anaerobic training” results in an increase in the W' without affecting the CP, with the increase in the W' likely resulting from an increased capacity for glycogenolysis (assumed due to a 34 % increase in post-exercise [Bla] following training; (Jenkins & Quigley, 1993). However, unlike their earlier research, Jenkins & Quigley (1993) identically replicated the power outputs at which to perform exhaustive CP predictive bouts post-training. Previously (Jenkins & Quigley, 1992), the power of the predicting trials had been increased so as to elicit T_{lim} within a similar duration-span following the training intervention. On this occasion (Jenkins & Quigley, 1993), the same powers were imposed post-training which resulted in the duration of the lowest-intensity exhaustive bout extending by at least 75 % (Pre-training = ~ 200 s; post-training = ~ 350 s). Furthermore, the longest predicting trial conducted pre-training was thus ~ 200 s, with the shortest trial lasting < 100 s. Predicting trials spanning this very narrow range and of such-short-duration will have resulted in elevated CP and reduced W' estimates (Bishop et al., 1998; Vandewalle, Vautier, Kachouri, Lechevalier, & Monod, 1997). In the control group, there was little change in the duration of the predicting trials pre- and post-training, which will have meant that any bias in the parameter estimates remained systematic. While in the training group, the marked increase in trial duration may have affected (particularly) the W' estimate, and as such, the observed ~ 50 % increase in W' may be somewhat ‘artificially’ inflated and should certainly be interpreted with caution.

Subsequently, Bishop & Jenkins (1996) went on to investigate the effect of six weeks of resistance training on the P-D parameters. Lower body resistance training for 90 minutes per session, 3 to 4 times per week, had no effect on the CP or $\dot{V}O_{2max}$ but did increase leg press 1-repetition maximum (1RM) by 29 % and the W' also showed a significant 35 % increase (unfortunately no

assessment of leg girth or muscle cross-sectional area was included). The increase in W' was strongly, negatively correlated with the small (non-significant) changes in CP ($r = -0.94$) which may help explain the reported 'no change' in time to exhaustion at CP following the training period (Bishop & Jenkins, 1996).

Following this series of publications by Jenkins and colleagues, there was over a decade without any notable publications supporting or refuting these findings. In 2008, and subsequent to the advent of the 3-min all-out cycling test, Vanhatalo and colleagues explored the effects of a mix of different interval-based training on both the conventional (CP & W') and all-out (EP & WEP) parameters of the P-D relationship. The 10 participants (2 female) trained three times per week for 4-weeks. Two of the training sessions involved completing six, 5-min intervals at 105 % of EP with 2.5 min active recovery between intervals. One session per week was similar to the 2-min high intensity intervals used by Gaesser & Wilson (1988) and Poole et al. (1990). However, Vanhatalo et al. (2008a) set the intensity of the 2-min interval such that at the completion of the first 2-min bout, 50 % of WEP should have been 'expended'. A 2-min active recovery separated each of the 10 intervals. As the training progressed, if participants were not achieving a peak HR within 10 bpm of (age-predicted) maximum HR during the final interval, the power output of the intervals was increased for subsequent sessions. This training regime resulted in a 10 % increase in EP, an 11 % increase in CP, a 9 % increase in $\dot{V}O_{2max}$ (all $P < 0.001$) and an 18 % increase in $GET_{(1, min^{-1})}$ ($P < 0.05$). There was no statistical difference in either the WEP (-4 %) or W' (-10 %) over the training period. Again, there was a significant, negative relationship between ΔCP and $\Delta W'$ ($r = -0.75$, $P = 0.02$). Importantly, the 3-min all-out test tracked the changes in CP, with EP being no different to CP at pre- or post-training. The WEP was not statistically different to W' pre- or post-training but the ΔWEP was significantly different to the $\Delta W'$ and the correlation between WEP and W' was non-significant post-training ($r = 0.63$, $P = 0.07$; pre-training: $r = 0.82$, $P = 0.007$).

The following year, Kendall et al. (2009) published experimental data suggesting that 4 weeks of interval training combined with creatine supplementation had beneficial effects on the CP parameter only. 16 male

participants underwent training & creatine (TCr), a placebo group (n = 16 men) underwent training & placebo (TPb) with an control group (Con) completing no training (n = 10 men). Training took place 5 days a week with 'easy' days taking place either side of 'hard' days of training. Easy training consisted of 5 to 6, 2-min bouts at 80 % $\dot{V}O_{2max}$ with 1 min rest between. Hard training progressed from 90 to 120 % $\dot{V}O_{2max}$ over the 4-week period and followed the same structure as easy training. CP significantly increased by 7 % in the TCr group, remained unchanged in the TPb group (+4 %) and significantly decreased in the Con group by 6 %. W' from the TCr, TPb and Con groups did not change with training (-5 %, 0 % & +15 % respectively). Despite measuring $\dot{V}O_{2max}$ before the training period, the measurement was not repeated, or the results not reported, after training. Furthermore, no details of the duration of the predicting trials used in the estimation of CP and W' are reported. The authors suggest that training volume may have been insufficient to induce an aerobic adaptation, yet the addition of creatine supplementation, which the authors acknowledge is of potential benefit to the W' parameter if anything, appeared to provide a distinct advantage to the CP parameter (Kendall et al., 2009). It is also confusing that the Con group (recreationally active, but not 'trained' males) exhibited a significant reduction in the CP parameter over the relatively short, four-week experimental period; providing some concern over the methods or reproducibility of the power output or T_{lim} of the ergometers or participants (respectively) used in this study. Feasibly, the very short, 15 min recovery permitted between each of the three exhaustive predicting trials will have played a role in affecting the T_{lim} of each participant (Ferguson et al., 2010; Ferguson et al., 2007; Skiba et al., 2012); whether this was a systematic error is not known.

One of the most recent training investigations using the P-D relationship as the outcome variable investigated the effects of resistance training on the CP and W' (Sawyer et al., 2014). Supporting the results of Bishop & Jenkins (1996), Sawyer et al. (2014) observed a significant 46 % increase in the W' (using the linear work vs. time model) while the CP was unaffected (albeit a 1 % reduction). A control group (n = 5) showed no changes in CP, W' or $\dot{V}O_{2max}$; $\dot{V}O_{2max}$ was also unaffected in the strength training group. Strength training incorporated a number of exercises targeting the lower and some upper

extremities, three times per week for 8 weeks. This resulted in significant strength gains (1-repetition maximum) of ~ 14 to 39 % across different exercises. CP & W' were derived using three mathematical models (non-linear hyperbolic, work vs. time and power vs. 1/time models) but the work vs. time model consistently provided the best mathematical fit ($R^2 \geq 0.990$) and the median CP and W' estimates. The authors correlated the change in W' ($\Delta W'$) to the change in T_{lim} (ΔT_{lim}) in the exhaustive predicting bouts, finding a consistent significant correlation between the two parameters for the three highest-power trials ($r = 0.64$ to 0.93 , $P < 0.013$); ΔCP was not correlated with ΔT_{lim} ($r = -0.21$ to 0.48 , $P > 0.154$) in the three highest-power trials but was significantly correlated to the ΔT_{lim} in the lowest-power predicting trial ($r = 0.72$, $P = 0.004$; (Sawyer et al., 2014)).

Together these training studies (summarised in Table 2.2 p49) which all used the P-D relationship to explore training-induced changes in the CP and W' parameters suggest that the CP can change independently from the $\dot{V}O_{2max}$ (Gaesser & Wilson, 1988; Jenkins & Quigley, 1992); that typically, increases in CP result in decreases in W' and vice versa (Gaesser & Wilson, 1988; Jenkins & Quigley, 1992; Kendall et al., 2009; Poole et al., 1990; Sawyer et al., 2014; Vanhatalo et al., 2008a); that the 'distance' between the CP and $\dot{V}O_{2max}$ may be related to the W' (Poole et al., 1990; Vanhatalo et al., 2008a) unless resistance training is employed, where the W' appears to be increased without affecting the $\dot{V}O_{2max}$ (Bishop & Jenkins, 1996; Sawyer et al., 2014) and that if any modality-specific (i.e. cycle) training is to be effective at enhancing the W', it is likely to be short-duration (≤ 60 s) and all-out in its execution (Jenkins & Quigley, 1993).

Table 2.3. Training-induced changes in $\dot{V}O_{2max}$, CP and W'.

Reference	n	Mode	Frequency (d/wk)	Weeks	Reps	Intensity	Work duration	Rest duration	Results
(Gaesser & Wilson, 1988)	5M	C	3	6	1	50 % $\dot{V}O_{2max}$	40 min	NA	↑ 13 % CP ↔ -6 % W' ↔ 2 % $\dot{V}O_{2max}$
	6M	C	3	6	10	100 % $\dot{V}O_{2max}$	2 min	2 min	↑ 15 % CP ↔ -7 % W' ↔ 5 % $\dot{V}O_{2max}$
(Poole et al., 1990)	8M	C	3	7	10	105 % $\dot{V}O_{2max}$	2 min	2 min	↑ 10 % CP ↔ 1 % W' ↑ 15 % $\dot{V}O_{2max}$
(Jenkins & Quigley, 1992)	12M	C	3	8	1	Avg Power for 40 min	30 to 40 min	NA	↑ 30 % CP ↔ -26 % W'
	6M	C	Con	8	NA	NA	NA	NA	↑ 8 % $\dot{V}O_{2max}$ ↔ 5 % CP ↔ -23 % W' ↔ 1.5 % $\dot{V}O_{2max}$
(Jenkins & Quigley, 1993)	8M	C	3	8	5	All-Out (0.736 N.kg ⁻¹)	1 min	5 min	↔ 3 % CP ↑ 49 % W' ↑ 10 % $\dot{V}O_{2max}$
	7M	C	Con.	8	NA	NA	NA	NA	↔ 2 % CP ↔ 6 % W' ↔ -1 % $\dot{V}O_{2max}$
(Bishop & Jenkins, 1996)	8M	C & Weight	3 to 4	6	1 to 15	1 to 15 RM	90 min	NA	↔ CP ↑ 35 % W' ↔ $\dot{V}O_{2max}$
	8M	C	Con.	6	NA	NA	NA	NA	↔ CP ↔ W' ↔ $\dot{V}O_{2max}$
(Vanhatalo et al., 2008a)	8M 2F	C	3	4	6 10	105 %EP (0.5*WEP)/120s + EP	5 min 2min	2.5 min 2 min	↑ 11 % CP ↔ -10 % W' ↑ 9 % $\dot{V}O_{2max}$
(Kendall et al., 2009)	16M	C+ Cr	5	4	5 to 6	80 & 90 to 120 % $\dot{V}O_{2max}$	2 min	1 min	↑ 7 % CP ↔ -5 % W'
	16M	C + Pb	5	4	5 to 6	80 & 90 to 120 % $\dot{V}O_{2max}$	2 min	1 min	↔ 4 % CP ↔ 0 % W'
	10M	C	Con	4	NA	% $\dot{V}O_{2max}$ NA	NA	NA	↓ -6 % CP ↔ 15 % W'
(Sawyer et al., 2014)	14M	C & Weight	3	8	3x 8 reps	8 RM	< 1 min	1.5 to 2 min	↔ -1 % CP ↑ 46 % W'
	5M	C	Con	8	NA	NA	NA	NA	↔ 0 % $\dot{V}O_{2max}$ ↔ 0 % CP ↔ 5 % W' ↔ $\dot{V}O_{2max}$
(Zelt et al., 2014)	11M	C	3	4	4 to 6	All-out	30 s	4.5 min	↑ 5 % CP ↑ 4 % $\dot{V}O_{2max}$
	12M	C	3	4	4 to 6	All-out	15 s	4.75 min	% $\dot{V}O_{2max}$ ↑ 7 % CP ↑ 8 % $\dot{V}O_{2max}$
	13M	C	3	4	1	65 % $\dot{V}O_{2max}$	60 to 75 min	NA	% $\dot{V}O_{2max}$ ↑ 9 % CP ↑ 13 % $\dot{V}O_{2max}$ % $\dot{V}O_{2max}$

M = male participants; **F** = female participants; **C** = cycling; **Cr** = Creatine supplementation; **Pb** = Placebo supplementation; **Weight** = weight/resistance training; **Con** = non-exercise control group; **RM** = repetition maximum; $\dot{V}O_{2max}$ = maximum oxygen uptake/exercise intensity eliciting corresponding percentage of maximum oxygen consumption; **All-Out** = maximal sprint effort; **EP** = end power from 3-min all-out test; **WEP** = work performed above end power during a 3-min all-out test; **CP** = critical power; **W'** = curvature constant of the power-duration relationship; ↑ = significant increase; ↔ = no change; ↓ = significant decrease.

2.9. Adaptations to Exercise Training; Enhancing 'Aerobic' Capabilities

Any alteration within the human body that enhances either, 1) the ability of the cardiovascular system to deliver oxygen to skeletal muscle, 2) the ability of skeletal muscle to extract and utilise oxygen for the resynthesis of ATP or, 3) continue neural drive to the exercising muscle despite contrary afferent feedback to the spinal cord and brain, has the potential to result in enhanced exercise performance. Exercise training has proved effective at driving adaptations in these global areas which, presumably, has direct or concomitant effects on the P-D relationship parameters. For comprehensive reviews of the signalling proteins and adaptive processes induced by various types of muscle action please see (Baar, 2014; Coffey & Hawley, 2007; Egan & Zierath, 2013; Wagner, 2011).

The efficacy of relatively short-duration (< 2 min) high-intensity exercise training has received increasing interest (Jacobs et al., 2013; Laursen & Jenkins, 2002). Indeed, it would appear that training that could be considered 'anaerobic' (repeated very high-intensity exercise bouts) may provide substantial metabolic and performance advantages for endurance exercise tasks. An excellent review paper detailing the performance alterations observed in response to both continuous and intermittent exercise training regimes in both healthy untrained participants and highly trained athletes was published in 2002 (Laursen & Jenkins, 2002). Below an extension and update of the table presented by Laursen & Jenkins (2002) is presented beginning with relevant publications from 2003 to present day (Table 2.4 p77).

Table 2.4. Training-induced changes in exercise performance.

An update (from Laursen & Jenkins (2002)) of recent experimental papers reporting the effects of various exercise training regimes on numerous exercise performance measures.

Reference	n	Mode	Frequency (d/wk)	Weeks	Reps	Intensity	Work duration	Rest duration	Results
(McKay, Paterson, & Kowalchuk, 2009)	6M	C	2	3	8-12	120% P _{ramp}	1min	1min	55%↑ T _{lim}
	6M	C	2	3	1	65% $\dot{V}O_{2max}$	90-120min	0.5-1.5min	43%↑ T _{lim}
	6M	Con	0	1	0	N/A	N/A	N/A	↔ T _{lim}
(Bailey et al., 2009b)	8M&F	C	3	2	4-7	All-Out	30 s	4min	50%↑ T _{lim}
	8M&F	C	3	2	1	90% GET	14-25min	0	↔ T _{lim}
	8M&F	Con	0	2	0	N/A	N/A	N/A	↔ T _{lim}
(Burgomaster et al., 2005)	8M&F	C	3	2	4-7	All-Out	30 s	4min	100%↑ T _{lim} , ↑ PPO
	8M	Con	0	2	0	N/A	N/A	N/A	↔ T _{lim}
(Serpello et al., 2012)	10M&F	R	3	4	15	All-Out	4 s	20 s reps 4.5min sets	13%↑ P _{avg} ↔ PPO
(Mohr et al., 2007)	6M	R	3-6	8	15	95% maxSp	6 s	1min	10%↑ YoYo 6%↑ 50m Sp ↔ T _{lim}
	7M	R	3-6	8	8	130% P _{ramp}	30 s	1.5min	29%↑ YoYo ↔ 50m Sp 15%↑ T _{lim}
(Jacobs et al., 2013)	16M	C	3	2	8-12	100% P _{ramp}	1min	75 s	7%↑ P _{ramp} 5%↑ P _{TT}
(Burgomaster, Heigenhauser, & Gibala, 2006)	8M	C	3	2	4-7	All-Out	30 s	4min	10%↑ P _{TT} 5%↑ PPO
	8M	Con	0	2	0	N/A	N/A	N/A	↔ P _{TT}
(Cocks et al., 2013)	8M	C	3	6	4-6	All-Out	30 s	4.5min	9%↑ P _{ramp}
	8M	C	5	6	1	65% $\dot{V}O_{2max}$	40-60min	0	16%↑ P _{ramp}
(Barnett et al., 2004)	8M	C	3	8	3-6	All-Out	30 s	3min	7%↑ P _{avg} 8%↑ PPO
	8M	Con	0	8	0	N/A	N/A	N/A	3%↑ P _{avg} 9%↑ PPO
(Zelt et al., 2014)	11M	C	3	4	4 to 6	All-out	30 s	4.5 min	~ 7%↑ PPO
	12M	C	3	4	4 to 6	All-out	15 s	4.75 min	~ 16%↑ PPO
	13M	C	3	4	1	65% $\dot{V}O_{2max}$	60 to 75 min	NA	~ 8%↑ PPO

M = male participants; **F** = female participants; **C** = cycling; **R** = running; **Con** = non-exercise control group; **P_{ramp}** = highest power achieved at the end of an incremental exercise test to volitional exhaustion; $\dot{V}O_{2max}$ = exercise intensity eliciting corresponding percentage of maximum oxygen consumption; **All-Out** = maximal sprint effort; **GET** = gas exchange threshold; **maxSp** = maximum sprinting speed; **T_{lim}** = time to exhaustion; **PPO** = peak power output (sprint effort); **P_{avg}** = average power output; **P_{tt}** = average power output during a simulated time trial; **YoYo** = yoyo-intermittent run test distance completed; **50m Sp** = 50 meter sprint test speed; ↑ = significant increase; ↔ = no change.

2.10. Anaerobic Adaptations to Exercise Training

Much like aerobic adaptations to exercise training, there are numerous alterations within the muscle as a result of 'anaerobic' training stimuli. The following section will outline some of the most notable cell signalling, enzymatic, fibre-type phenotypic and ultimately performance alterations in response to training that can be considered predominantly 'anaerobic'.

2.10.1. Muscle fibre type

As with cellular signalling implicated in the various muscular adaptations to endurance training, the same metabolites play roles in activating transcriptional co-activators, which play a role in affecting the gene transcription for muscle fibre type. The exact mechanisms of fibre type changes in response to environmental cues are not fully elucidated and are beyond the scope of this thesis. However, Gundersen (2011) presents a valiant attempt to diagrammatically depict this complex interaction of environmental cues, sensory proteins responsible for signalling the adaptive cascade and the transcriptional factors thought to be responsible for muscle phenotypes. Events such as not only the magnitude of $[Ca^{2+}]_i$ peaks but also the duration of $[Ca^{2+}]_i$ fluctuations are thought to play a key role in the direction of muscle phenotype signalling (Gundersen, 2011). In this sense, it would once again appear that the intensity and duration of muscle contraction play a key role in the adaptive response of the muscle fibre pool to the training performed.

With 'anaerobic' training, exercise is typically very short ($\leq 30 - 45$ s) and all-out (supra-maximal). Conversely, 'strength and power training' is typically performed as resistance/weight training. While there is much literature available detailing the key transcriptional and 'master regulators' of resistance training and the desired hypertrophic and strength adaptations desired from this type of training, it is again outside the scope of this thesis. However, whole body, dynamic exercise performed for short durations at supra-maximal intensities has proven to be a potent stimulus for metabolic and muscle fibre alteration (Gibala, 2009; Gibala & McGee, 2008; Jacobs, Esbjornsson, Sylven, Holm, & Jansson, 1987; MacDougall et al., 1998).

2.10.2. Muscle glycogen

During a 30 s supramaximal cycling bout ~ 30 % of ATP is derived via oxidative metabolism, ~ 25 % from resting ATP and the rapid hydrolysis of PCr and ~ 50 % from glycolysis (Bogdanis, 2012; Bogdanis, Nevill, Boobis, & Lakomy, 1996a). Following a 4-min recovery, during a second 30 s supramaximal sprint these relative contributions change to ~ 45 %, 20 % and 35 % respectively, showing quite nicely how aerobic ATP resynthesis begins to contribute more predominantly and anaerobic glycolysis' contribution is diminished somewhat. Resting adult skeletal muscle contains ~ 4 mmol.kg wm^{-1} ATP and ~ 15 mmol.kg wm^{-1} PCr (Gollnick & Hermansen, 1973; Withers et al., 1991). The recovery of PCr is rapid and is determined by the oxidative capacity of the muscle whereby in endurance trained muscle, the half time of PCr resynthesis can be as short as ~ 13 s which can be twice as quick as in untrained muscle (Johansen & Quistorff, 2003). The recovery of the glycolytic system is less straightforward as muscle glycogen stores are finite at exercise onset (Bergstrom et al., 1967; Jeukendrup, 2004; Katz & Westerblad, 2014). Following a single 30 s supra-maximal cycle bout, muscle glycogen content can decrease by ~ 30 – 34 % (Bogdanis et al., 1996a; Bogdanis et al., 1995) and by a further ~ 24 % over the course of a second bout some 4 minutes later (total reduction in muscle glycogen ~ 44 %; (Bogdanis et al., 1996a)). While there is some strong evidence to suggest that muscle glycogen synthesis does occur following high-intensity exercise even in the absence of carbohydrate consumption (Fairchild et al., 2003; Raja, Brau, Palmer, & Fournier, 2008), there is a paucity of research examining the acute (0 to 5 min post exercise) synthesis of muscle glycogen following supramaximal exercise bouts. However, there is some evidence that there is negligible (~ 4 to 6 %) muscle glycogen resynthesis in the 6 min following a supramaximal 30 s cycle bout (Bogdanis et al., 1995; Bogdanis, Nevill, Lakomy, Graham, & Louis, 1996b). This observation was under passive rest following a 30 s supramaximal exercise bout. Other authors have investigated the fibre-specific muscle glycogen resynthesis during moderate-intensity 'active recovery' subsequent to a 3 min high-intensity exercise bout and reported that, compared to passive recovery, active recovery slows the rate and magnitude of muscle glycogen synthesis (Fairchild et al.,

2003). Furthermore, there is likely a dampened muscle glycogen resynthesis in the muscle fibres recruited during an active recovery, whilst the 'inactive', usually higher order Type II fibres, are unaffected when the intensity of active recovery is sufficiently low (Fairchild et al., 2003).

There is conflicting evidence surrounding the importance of muscle glycogen for short-duration, extreme- or severe-intensity exercise performance (Maughan & Poole, 1981; Withers et al., 1991). Intuitively there should be a link between muscle glycogen content and high-intensity exercise performance (Krustrup et al., 2006). It has however been acknowledged that for a single high-intensity exercise bout, muscle glycogen appears not to be a limiting factor (Bangsbo, Graham, Kiens, & Saltin, 1992). Whereas, it is reasonably well established that greater muscle glycogen content, or certainly limiting the decline in muscle glycogen during prolonged 'endurance exercise', leads to faster completion times for given distances and higher average power for given durations (Coyle, Coggan, Hemmert, & Ivy, 1986; Ivy, Res, Sprague, & Widzer, 2003; Jeukendrup, 2004). With anaerobic training there is little evidence of increased resting muscle glycogen storage (with the exception of untrained participant studies (Burgomaster et al., 2006; Gibala et al., 2006) and one example in trained participants, showing a 15 % increase; (Shepley et al., 1992)) resulting from anaerobic training (Iaia et al., 2008). As detailed in section '2.6.1; 4) *Muscle Glycogen Content*', it is not well understood how altering the muscle glycogen content is likely to alter the P-D parameters.

2.10.3. *Glycolytic enzymes*

Despite resting muscle glycogen content being seemingly robust to anaerobic training and perhaps more importantly, the lack of evidence linking muscle glycogen content to short-duration sprint/exercise performance, it is commonplace to observe an increase in sprint/short-duration exercise performance following anaerobic training (Iaia & Bangsbo, 2010). As such, rather than the volume of muscle glycogen present in the muscle prior to a performance trial, perhaps an increased rate of glycogenolysis and anaerobic glycolysis help contribute to the enhanced exercise performance. However, while biochemically, increases in the number and activity of enzymes involved

in anaerobic glycolysis (Glycogen phosphorylase, PFK, glyceraldehyde-3-phosphate dehydrogenase (GAPDH), pyruvate dehydrogenase & lactate dehydrogenase) should result in a greater potential for anaerobic glycolysis, the response of these enzymes to anaerobic training is somewhat variable. While one study reports quite marked increases in PFK, glycogen phosphorylase, GAPDH and lactate dehydrogenase, along with a 25 % improvement in a 40 s performance running task (Roberts, Billeter, & Howald, 1982), the majority of research into anaerobic training and glycolytic enzyme alterations report little substantial positive or negative change (Bangsbo, Gunnarsson, Wendell, Nybo, & Thomassen, 2009; Houston & Thomson, 1977; Iaia et al., 2008). Interestingly in each of these instances, despite no notable change in anaerobic enzyme content or activity within the exercising muscle, in all cases, exercise performance (which range from a 30 s maximal sprint run, to 60 and 90 s all-out runs through to a 10 km run) was increased significantly as a result of the 'anaerobic training'. Thus, in the absence of any enhanced glycolytic capabilities, authors have been forced to explore other areas of explanation for these enhanced 'anaerobic' performances (outside of the prevalent enhancements in $\dot{V}O_{2\text{peak}}$, mitochondrial biogenesis, capillarisation and oxidative enzyme activities). One such explanation is muscle-buffering capacity.

2.10.4. Muscle buffering

With severe- and extreme-intensity exercise at a constant-power output, there is a progressive and inexorable increase in intra- and extracellular metabolites which both help regulate metabolism and inhibit the force-producing capability of the muscle (Allen et al., 2008b; Enoka et al., 2011). This reduction in force within the muscle is multifaceted in its aetiology but manifests itself as 'fatigue'. While there is still much to learn about muscle fatigue, the current best understanding implicates a number of specific metabolites (P_i , Na^+ , K^+ , Ca^{2+} and H^+), some of which can be 'buffered' or better tolerated by the exercise-trained muscle (Mohr et al., 2007). It is well known that intracellular P_i accumulation has an inhibitory role on the SR, preventing the resequestering of Ca^{2+} , resulting in elevated $[Ca^{2+}]_i$, but reduced SR Ca^{2+} to release in subsequent muscle actions, leading to a lower force output of the muscle (Westerblad et al., 2002). However, P_i plays many other vital roles in energy

metabolism, for example P_i closely mirrors, and is believed to be one of the drivers of oxygen uptake (Rossiter et al., 2002; Whipp, Ward, & Rossiter, 2005). Furthermore, 'buffering' of P_i *per se* is fruitless as P_i accumulates as a result of PCr hydrolysis, required to maintain muscle ATP homeostasis. While pharmacological intervention (2, 4-dinitro-1-fluorobenzene) or genetic deletion of genes can inhibit and prevent the CK reaction respectively, this is not an ergogenic strategy for high-intensity exercise performance. Indeed, genetic deletion of CK results in higher resting P_i concentration within the muscle and a concomitant lower muscle force producible from tetanic contractions (Dahlstedt, Katz, Wieringa, & Westerblad, 2000). This, along with other evidence, strongly links P_i with muscle fatigue (Westerblad et al., 2002) but the 'buffering' of P_i isn't biochemically viable. H^+ however, lends itself well to a biochemical buffer and indeed, the $NaHCO_3$ buffer system provides much 'tolerance' to anaerobic exercise induced H^+ accumulation. There is some evidence that consumption of substances which cause alkalosis within the body reduce the rate of fatigue within the muscle. However, increased alkalosis appears to exert its fatigue-delaying effect through decreasing extracellular $[K^+]$, thus maintaining membrane excitability and muscle innervation (Sostaric et al., 2006). Intracellular buffering of H^+ via muscle carnosine (β -alanine supplementation) may also delay fatigue but it would appear that carnosine might greatly increase the Ca^{2+} sensitivity of SR, t-tubules and sarcolemma (Dutka & Lamb, 2004; Hill et al., 2007). Both of these buffer-induced changes to muscle action are advantageous to sustained high-intensity exercise performance as elevated H^+ /decreased intra-cellular pH is linked to a reduced shortening velocity of actin, independent of temperature (Debold, Beck, & Warshaw, 2008; Knuth, Dave, Peters, & Fitts, 2006). However, repeated sprint/high-intensity exercise training *per se* appears to have no effect on muscle carnosine content (McLean et al., 2013), but intra-muscular stores may increase as muscle fibre composition increases its type II fibre content (Harris et al., 2012). Furthermore, there is little evidence that exercise training increases the $NaHCO_3$ availability either, yet through increased Na^+ - K^+ -ATPase activity, exercise training may help the muscle better deal with elevated H^+ or lowered pH-induced excitation/shortening velocity reduction issues (Edge et al., 2013). To this end, Mohr and colleagues (2007) compared the intramuscular and performance changes in response to either very short (6 s) repeated sprint running (95 %

max speed) or 30 s 'speed endurance' running (130 % speed at $\dot{V}O_{2peak}$) for 8 weeks (30 sessions). Short-duration, maximal exercise performance (50 m sprint) was improved only in the sprint group whereas endurance time during an incremental exercise protocol was only enhanced in the speed endurance group. The authors attribute endurance performance improvements to elevated Na^+K^+ -ATPase $\alpha 2$ -isoform on the sarcolemma; as only speed endurance training resulted in an increase in this specific isoform, which may have helped to regulate the extracellular increase in K^+ with prolonged endurance performance. In the sprint group, higher muscle CK was observed following 8 weeks of training and this was then postulated to have contributed to the enhanced short-duration exercise performance observed in the sprint group (Mohr et al., 2007). What is quite interesting from this experimental paper is the quite distinct differences in skeletal muscle adaptation even between training intervals differing by only ~25 s in duration, indicating the quite specific nature of adaptation within the muscle to the exercise stimulus received.

2.11. Effect of Inspired Oxygen Fraction on the CP and W'

Since the earliest dynamic whole body work investigating the P-D relationship (Moritani et al., 1981), there has been interest in the effect of inspired O_2 fraction (F_iO_2) on both the P-D parameters and exercise performance. Initially, the effects of two hypoxic inspirants (0.12 & 0.09) were compared to room air (0.2093) in just two participants (Moritani et al., 1981). In these two examples, a 0.09 F_iO_2 resulted in a 50 ± 8 % reduction in CP, whilst the W' (intercept of the Work vs. time model) was relatively unaffected. Data from the 0.12 F_iO_2 was not presented numerically. The next published investigation explicitly characterising the P-D relationship in response to altered F_iO_2 was published in 2010 (Vanhatalo et al., 2010a). Here, rather than reduce the F_iO_2 , Vanhatalo et al (2010) increased the F_iO_2 to 0.70 and compared the hyperoxic P-D CP and W' to the normoxic equivalents with the hypothesis that CP would be increased and the W' unaffected. Additionally, this study was conducted using knee extension exercise in the bore of a 1.5 Tesla super-conducting magnet capable of non-invasively measuring muscle metabolites. The authors hypothesised that PCr and pH would fall and P_i rise toward a critical level at which severe intensity

exercise would cease and that this critical level (while taking longer-durations to reach in hyperoxia) would be independent of F_iO_2 . This latter hypothesis was confirmed, and as such provides excellent experimental support for the W' 'accumulation' hypothesis. However, their first hypothesis, that CP would be enhanced without affecting W' was not fully confirmed. The CP, as expected, was increased with hyperoxia (normoxia: 16.1 ± 2.6 vs. hyperoxia: 18.0 ± 2.3 W; 12.4 ± 10.5 % significant increase). However, the W' was reduced (normoxia: 1.92 ± 0.70 vs. hyperoxia: 1.48 ± 0.31 kJ; -18.7 ± 16.5 % significant decrease). The ΔCP and $\Delta W'$ were significantly negatively correlated ($r = -0.88$, $P < 0.05$). Therefore, Vanhatalo et al. (2010) had also provided some support (although $\dot{V}O_{2max}$ was not assessed) for the W' 'size of the severe domain' hypothesis.

Subsequently, the effects of moderate hypoxia on the P-D parameters, as studied by Moritani et al (1981), was re-addressed in a larger participant pool (Dekerle et al., 2012). Dekerle et al (2012) reported a 12 ± 5 % reduction in $\dot{V}O_{2max}$ and a 14 ± 6 % reduction in CP when incremental and exhaustive P-D trials were performed with an F_iO_2 of 0.15. There was a non-significant (3 %) increase in W' with the hypoxic condition but this mean change masked the large inter-individual differences in response, which ranged from -36 % to 66 % differences in W' due to the hypoxic inspirit. The reduction in CP is not surprising. At an F_iO_2 of ~ 0.209 , the partial pressure of inspired O_2 (P_iO_2) is ~ 149 mmHg with the partial pressure of arterial O_2 (PaO_2) being ~ 100 mmHg due to gas mixing (Wilber, 2004). When the F_iO_2 is reduced (e.g. 0.15), P_iO_2 is also reduced (e.g. 120 mmHg) and concomitantly PaO_2 is reduced somewhat below the 100 mmHg expected at an F_iO_2 of 0.209. This has obvious consequences for tissue-level PO_2 and creates a smaller pressure gradient forcing O_2 into the oxidative machinery of the cells (Wilber, 2004). While normobaric hypoxia (simulated altitude or lowered F_iO_2) and hypobaric hypoxia (F_iO_2 unchanged, but atmospheric pressure is reduced creating a lower PO_2) appear to have almost identical physiological effects within the O_2 delivery and utilisation pathways (Wagner, 1996), it is interesting to note the results of one other investigation into the effects of ascent to altitude on the P-D relationship (Valli et al., 2011). Valli et al. (2011) took six participants (two females) to 5050 m (equivalent to an F_iO_2 of ~ 0.107) at the CNR Pyramid Laboratory, Nepal.

Following a gradual acclimation process over 14 days, participants undertook incremental and three constant-power exhaustive trials to characterise the $\dot{V}O_{2max}$ and P-D relationship respectively. Compared to sea level, CP, $\dot{V}O_{2max}$ & W' were significantly reduced by 34 % (P = 0.04) 32 % (P = 0.007) and 82 % (P = 0.02) respectively. These changes in the P-D parameters occurred in the absence of any significant differences in the T_{lim} of the exhaustive constant-power trials performed at sea level and at 5050 m and thus are difficult to explain based on the data provided. However, in the representative data presented in fig 2 (p 338 (Valli et al., 2011)), it would appear that $\dot{V}O_{2max}$ was not attained during the lowest-intensity exhaustive exercise bout, despite reaching T_{lim} ; suggesting that exercise was terminated prior to reaching 'failure'. This phenomenon has been observed at similar F_iO_2 (0.10) where it would appear central motor drive down-regulates the force a muscle is able to produce sometime prior to peripheral metabolites approaching levels associated with reduction in muscle force (Amann, Romer, Subudhi, Pegelow, & Dempsey, 2007). Therefore, the severity of the altitude used by Valli et al. (2011) may well have prevented the characterisation of the P-D relationship based on peripheral fatigue, which, for the time-span of exercise durations in the severe-intensity domain (~ 2 to 45 min; (Burnley & Jones, 2007)) are the prevailing cause of exercise intolerance (Amann, 2011; Decorte et al., 2012). However, at moderate (simulated) altitude, peripheral mechanisms appear to be the predominate cause of fatigue (Amann et al., 2007), and as such, the studies of Moritani et al. (1981) and Dekerle et al. (2012) would concur with the theoretical response of the P-D relationship to a reduction in F_iO_2 ; that being a reduced oxidative capacity affecting both the maximal rate of O_2 uptake and the maximal 'steady state' O_2 uptake (CP), while not affecting the quantity of work which may be performed above the CP. In that sense moderate hypoxia pertains to a useful model to 'test' the interactions between $\dot{V}O_{2max}$, CP and the W' parameters. Furthermore, the 3-min all-out test has yet to be used in either hypoxic or hyperoxic conditions; the all-out test may prove a rapid and insightful method of understanding the interplay between $\dot{V}O_{2max}$, CP and the W'.

2.12. Aims and Hypotheses

The above review highlights the ability of the CP and W' to, together, characterise exercise tolerance within the severe-intensity domain irrespective of whether the CP or W' were obtained via conventional or all-out methods. Furthermore, the importance of the W' in determining exercise performance capabilities over relatively short durations ($< \sim 7$ min) is such that the likely physiological explanations and response of this parameter warrants further investigation. The CP concept dictates that for a known power output sustained $> CP$ for a known duration, a calculable reduction in the W' will be observed (Fukuba et al., 2003). This principle provides an opportunity to test the ability of the 3-min test to detect such induced reductions in the W' prior to test onset. In doing so, it would also answer the question as to whether the 3-min all-out test provides reliable EP and WEP parameters when initiated from an elevated metabolic 'baseline' period; as all published research to date has initiated the all-out test from an 'unloaded' baseline period (Bergstrom et al., 2013b; Chidnok et al., 2013a; Vanhatalo et al., 2007, 2008a, 2008b; Vanhatalo & Jones, 2009b; Vanhatalo et al., 2010b; Vanhatalo et al., 2011).

Severe-intensity exercise tolerance, and the W' , appear to be reduced under restricted muscle glycogen conditions. At the upper extreme of the heavy-intensity domain (an intensity approaching CP), muscle glycogen oxidation rates are appreciably higher than at moderate-intensity (van Loon et al., 2001). Furthermore, as limited muscle glycogen stores also reduce exercise tolerance within the heavy-intensity domain (Bergstrom et al., 1967), muscle glycogen may also have a role in determining the magnitude of the CP parameter. By specifically targeting muscle glycogen depletion in type I or type II muscle fibres, the EP and WEP parameters (respectively) could be reduced. The 3-min all-out test enables this to be tested without requiring some 21 visits to the laboratory and repeated arduous glycogen depleting bouts and may provide further evidence pertaining to a potential constituent(s) of the W' .

Whereas glycogen depletion is thought to affect, predominantly, the W' parameter of the P-D relationship, hypoxia would appear to have little effect; rather, the lower P_{iO_2} is likely to reduce the CP parameter (Dekerle et al., 2012;

Moritani et al., 1981). The hypoxic environment provides a reasonably robust circumstance with which to assess the ability of the 3-min all-out test to track changes in the CP. However, based on existing all-out literature (Vanhatalo et al., 2008b) it may be necessary for the all-out test resistance to be manipulated to provide valid estimates of the W' . Furthermore, the hypoxic environment should allow for the assessment of whether the W' does reflect the 'size' of the severe-intensity domain, which is emerging as one of the more prominent explanations of the W' (Burnley & Jones, 2007; Vanhatalo et al., 2010a).

Finally, while the majority of the existing evidence suggests that the CP parameter will respond to exercise training, there is a paucity of evidence for positive training-induced changes in the W' . Aside from resistance training, only one example exists (Jenkins & Quigley, 1993). The emerging popularity of repeated sprint interval training (SIT), similar to that used by Jenkins and Quigley (1993), has resulted in a number of publications suggesting that SIT can result in substantial increases in high-intensity T_{lim} (Bailey et al., 2009b; Burgomaster et al., 2005). It is not presently known whether this increase in T_{lim} is a result of an enhanced CP or a larger W' , or perhaps some combination of both. Given the relative importance of the W' in determining short-duration (< ~ 7 min) endurance performance, a training-induced increase in this parameter would (i) help explain the increases observed in T_{lim} and, (ii) be an attractive method of relatively acutely enhancing exercise performance. If the 3-min test is to be a useful tool for assessing adaptations and alteration in athletes' physiology in response to training, then the all-out test will need to track training induced changes in CP and W' as a result of SIT. It is hypothesised that SIT will increase both the CP and W' compared to a training 'control' designed to increase only the CP, and that the 3-min all-out test parameters will faithfully track these changes.

2.12.1. Research questions & hypotheses

Q1.1 Does the 3-min all-out test WEP parameter remain unchanged and reduce by expected amounts when the 3-min all-out test is immediately preceded by sub- and supra-EP exercise respectively?

H1.1 The 3-min all-out test WEP parameter will be reduced by a calculated amount by severe-intensity 'elevated baseline' power output prior to commencement of the 3-min all-out test.

Q1.2 Is the EP parameter of the 3-min all-out test altered by immediately prior exercise of moderate-, heavy- or severe-intensity exercise?

H1.2 The EP parameter of the 3-min all-out test will be unaffected by initiating the all-out test from elevated baseline power outputs.

Q2.1 Does muscle glycogen depletion of type II muscle fibres result in a reduction in 3-min all-out test WEP?

H2.1 Type II muscle fibre-specific glycogen depletion will result in a reduction in the WEP parameter of the 3-min all-out cycling test while the EP parameter will be unaffected.

Q2.2 Does muscle glycogen depletion of type I muscle fibres result in a reduction in the all-out test EP?

H2.2 Type I muscle fibre-specific glycogen depletion will result in a reduction in the EP without affecting the WEP of the 3-min all-out test.

Q3.1 Will moderate hypoxia cause a reduction in the $\dot{V}O_{2max}$ and EP of the all-out test without affecting WEP?

H3.1 Under moderate hypoxia, the $\dot{V}O_{2max}$ and EP will be reduced while the WEP will be unaffected compared to normoxia.

Q3.2 Does the 3-min all-out test ergometer require a 'hypoxic specific' resistance in order for WEP and W' to be of similar magnitude?

H3.2 When the normoxic ergometer resistance is used in hypoxia, the WEP will be overestimated yet the EP will be the same as the EP obtained when a hypoxic-specific ergometer resistance is used. WEP from the hypoxic-specific test will not be different to W' .

Q3.3 Does moderate hypoxia similarly reduce $\dot{V}O_{2max}$ and EP and is the difference between these two parameters associated with the magnitude of the W' ?

H3.3 The relative change in $\dot{V}O_{2max}$ and EP will be such that the 'size' of the severe-intensity domain is unchanged in hypoxia.

Q4.1 Does SIT induce alterations in both the power-duration relationship?

H4.1 SIT training will induce significant increases in $\dot{V}O_{2max}$, EP and WEP

Q4.2 Will END affect WEP?

H4.2 Constant-power endurance training will result in increases in $\dot{V}O_{2max}$ and EP without affecting the WEP.

Q4.3 Will SIT and END induce similar alterations in the power-duration relationship despite different training time commitments?

H4.3 SIT and endurance training will result in similar enhancements in $\dot{V}O_{2max}$ and EP despite a markedly shorter time commitment for SIT.

Chapter 3 - General Methods

3.1. Health and Safety

The procedures of each experimental chapter within this thesis were approved by the local ethics committee of the University of Exeter prior to commencement of data collection.

All non-disposable equipment coming into contact with participants and the surfaces of the testing laboratory were kept clean and sterilized using Milton sterilizing solution (Milton, Newmarket, UK), according to manufacture's guidelines. Any non-disposable equipment that became contaminated with blood was treated with and disinfected using Virkon sterilizing solution (DuPont Rely+On Virkon, Colchester, UK). Blood waste, from laboratory blood analysis equipment, was disposed of according to the guidelines of the laboratory, as prescribed by professional technicians employed by the University. The blood waste location was kept separate from the sterilization of respiratory equipment.

All capillary blood samples were initiated via the use of a safety lancet with self-retracting, 1.6 mm deep blade (safety-lancet Super, Sarstedt AG & Co., Numbrecht, Germany). Once used, lancets were safely disposed of into a clinical sharps container, stored higher than 1 m from floor height. Medical grade latex gloves were worn when piercing human skin or collecting capillary blood samples. All participants were screened (via questionnaire) for all allergies (including latex) prior to commencing each study. If a latex allergy was identified, non-allergenic, latex-free, nitrile gloves were available as required; no participants had a latex allergy. Consumables and tissues etc. contaminated with human blood were safely disposed of into clinical waste bins. The content of these bins was safely incinerated on a regular basis.

All exercise testing and training took place in an air-conditioned laboratory, maintaining ambient temperature at 20 ± 2 °C. Exercise testing for a given participant took place at the same time of day (± 3 hrs) and was preceded by a minimum of 24 hrs having avoided strenuous or exhaustive exercise and the consumption of alcohol. In the 3 hours preceding each test occasion,

participants avoided the consumption of caffeine and large meals and arrived at the laboratory in a well-hydrated state. These conditions were verbally checked with each participant upon arrival at the laboratory on each test occasion.

3.2. Participants

All participants volunteered to partake in experimentation and were recruited from the University undergraduate, postgraduate and staff cohorts as well as local cycling clubs. All participants and potential participants received written details of the study they would be volunteering for; including the reasons for conducting the research, the aims of the study, the number of visits required to the laboratory, the risks and benefits of participation and the testing and physical sensations likely involved with the testing to be conducted. It was clearly stated that withdrawal from participation was permitted at any time without reason or negative consequence. Prior to commencing any exercise testing, both a physical activity readiness questionnaire (PAR-Q) and a cardiovascular disease risk factor assessment were completed by each participant, as part of which each participant had their stretch stature (Harpenden stadiometer, Holtain, Crymych, UK), mass (Seca 799, Seca gmbh & co, Hamburg, Germany) and blood pressure (Welch Allyn DS54, Aston Abbots, UK & Unbranded Stethoscope, Hab International, Southam, UK) measured.

3.3. Cycle Ergometers

All exercise testing was completed on an electromagnetically-braked cycle ergometer (Lode Excalibur Sport, Lode, Groningen, Netherlands). All exercise testing with the exception of 3-min all-out tests were completed using the hyperbolic mode of the ergometer, where the power output imposed by the ergometer is independent of pedal cadence within the cadence range of 30 to 120 rpm (Does, 2013). On the initial visit to the laboratory, all participants had the ergometer position adjusted for comfort with these settings then replicated for all further testing occasions. Where desired, the ergometer pedals were swapped for specific cycling pedals allowing for the attachment of a cycling

shoe to the pedal without the use of toe straps. When cycling pedals were not used, all participants wore sports footwear and had their feet securely fastened into the ergometer platform pedals using toe straps. All exercise testing began with at least 3 minutes of cycling at a 'zero watt' baseline. For 3-min all-out testing, the ergometer was switched from hyperbolic mode to linear mode at the onset of the 3-min maximal effort. The ergometer was programmed to switch back to hyperbolic mode at a power output of 50 W once 180 s had elapsed (see section 3.6 for further details).

3.4. Ramp-Incremental Test

Following written informed consent and pre-exercise screening, each participant underwent a ramp-incremental exercise test to volitional exhaustion during their initial visit to the laboratory. The test began with a 4 min period of 'unloaded' cycling before the commencement of the ramp-increase in resistance imposed by the ergometer. The resistance increased at a rate of 30 (25 for females) $\text{W}\cdot\text{min}^{-1}$ (1 W (0.83 W for females) every 2 s) until the participant could no longer sustain their individually selected 'preferred cadence' within 10 rpm for over 5 s despite strong verbal encouragement from the experimenter present. At exhaustion, the elapsed time and power output were recorded. Peak incremental ramp power (P_{ramp}) was calculated by subtracting two thirds of the ramp-rate (in this case 20 W; 17 W for females) from the final power at which exhaustion occurred. This adjustment was also made for the power output at which the GET occurred and was required due to the time delay between pulmonary $\dot{V}\text{O}_2$ representing the energy cost of the external mechanical power output (Whipp et al., 1981).

The $\dot{V}\text{O}_{2\text{peak}}$ was determined as the highest average $\dot{V}\text{O}_2$ over a 30 s period. Pulmonary data were reduced to serial 10 s average time bins for the estimation of the GET using the method described by Beaver et al. (1986) and detailed more fully in section 1.3 'Lactate Threshold'. At least two, and typically three, independent investigators each reviewed the pulmonary gas exchange data time aligned to the ergometer power output data for identification of the GET. Each investigator's determination was subsequently marked on the original file,

focusing the final GET determination down to a common and agreed $\dot{V}O_2$ and power output. An example of this process is depicted in Figure 3.1 p93.

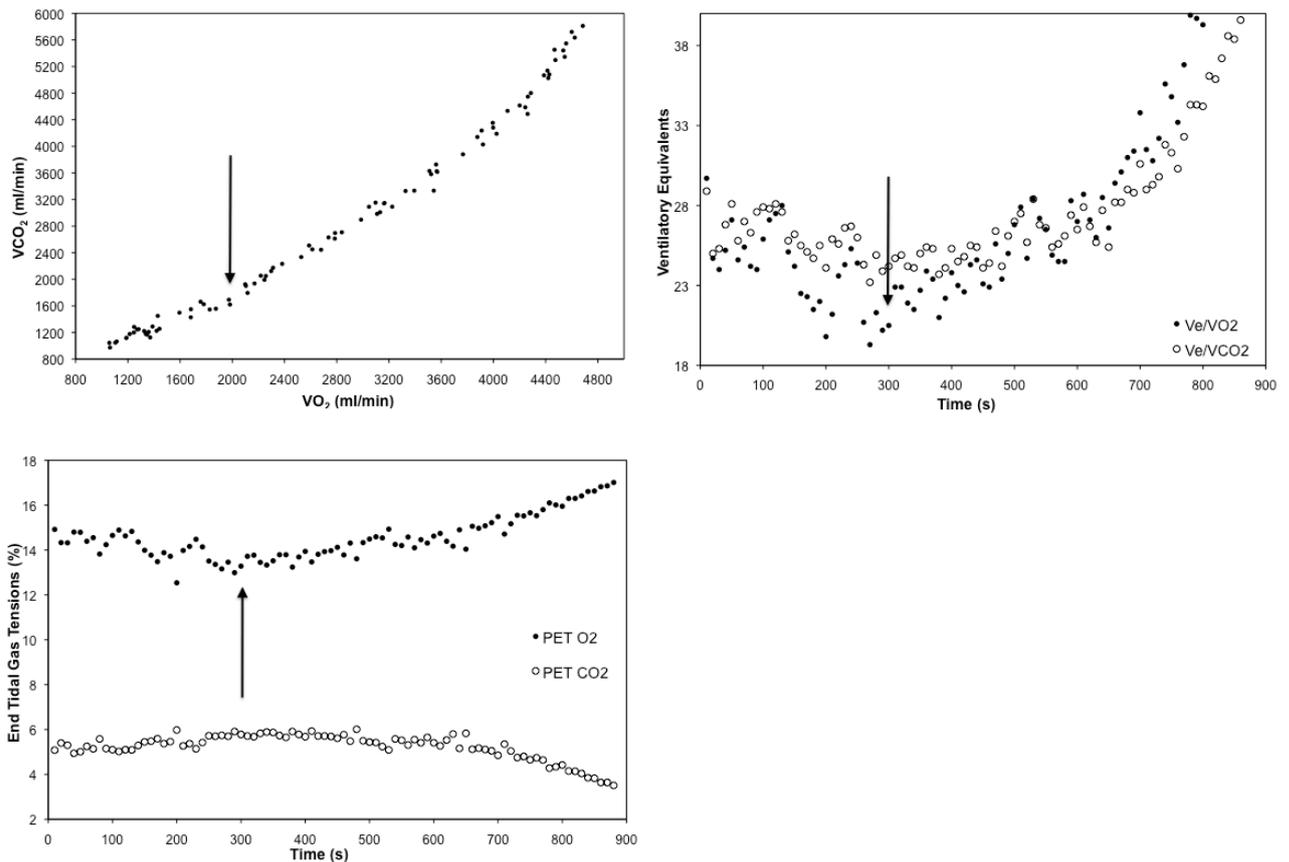


Figure 3.1. GET Determination.

Three plots of pulmonary gas data from a single participant in response to ramp incremental exercise. These plots are used for the determination of the GET. Clockwise from the top left; $\dot{V}CO_2$ Vs. $\dot{V}O_2$; ventilatory equivalents Vs. duration; end tidal gas tensions Vs. duration. The arrow in each plot indicates the point at which the GET has been identified based on the data exclusively in that plot. The equivalent power and $\dot{V}O_2$ for the duration identified (in this case 300s) is then marked on the raw data, effectively honing in on a common time, power and $\dot{V}O_2$ at which the GET occurred.

3.5. Normalising Exercise Intensities

Following the calculation of the power output equating to the GET and P_{ramp} , all subsequent exercise intensities were set relative to these two parameters. Moderate-intensity exercise was set as a percentage of GET (i.e. below GET); for example 80 % GET was calculated as $\text{GET} \times 0.8$. Severe-intensity exercise, as used for the conventional determination of CP and W' through a series of

exhaustive exercise bouts, was set at intensities between 60 and 95 % Δ . These were calculated as (in this case with 65 % Δ as the example):

$$((P_{\text{ramp}} - \text{GET}) \cdot 0.65) + \text{GET} \quad [3.1]$$

Prior to the determination of the CP or EP, heavy-intensity exercise was determined as 5 to 40 % Δ . However, once EP or CP had been determined, this enabled heavy-intensity exercise to be set according to the 'Delta 2' concept. Here, the difference between the CP or EP and the GET is calculated and a given fraction of that difference is added to the GET. For example, the 'middle' of the heavy-intensity domain would be 50 % Δ and would be calculated as:

$$((\text{CP} - \text{GET}) \times 0.5) + \text{GET} \quad [3.2]$$

In some instances, to induce exhaustion within a sufficiently short duration (~ 3 min), exercise intensities of greater than the P_{ramp} were required. Here the intensity was set as 105 to 120 % P_{ramp} .

3.6. 3-min All-Out Test

The 3-min all-out cycling test is typically performed following a period of unloaded or moderate-intensity cycling (hyperbolic mode). The participant is informed as to when the maximal sprint will begin during this period. With ~ 10 s to go the participant is told to raise cadence to 100 to 120 rpm in order to reduce the inertia which must be overcome at the commencement of the all-out sprint. At the point that at which the 'all-out' portion of the 3-min all-out test begins, the ergometer instantaneously changes into 'linear mode' creating a fixed resistance, equivalent to riding a single-gear bicycle up a hill of constant gradient. The linear setting of the ergometer is adjusted by changing the linear factor (see equation 3.3) which effectively sets both the 'gear' of the bike and the 'gradient' of the hill, providing a directly proportional relationship between pedal rate and torque output (Figure 3.1 p93). The linear torque vs. cadence relationship results in an exponential relationship between power output and cadence (Figure 3.2 p95), much like the relationship between power and bike

speed during 'real world' cycling (Martin et al., 2006). Once the 3-min duration has elapsed, the ergometer instantaneously changes back to hyperbolic mode, imposing a moderate-intensity power output for the participant to continue cycling against should they wish.

$$\text{Linear Factor} = \text{power output}/(\text{cadence}^2) \quad [3.3]$$

Whereby, for example, a linear factor of 0.030 would equate to a power output of 300 W at a cadence of 100 rpm. The linear factor is adjustable between the range of 0.010 to 0.300. The linear factor is chosen such that at a participant's preferred pedal rate, a power output equivalent to 50 % Δ would be achieved (Burnley et al., 2006a; Vanhatalo et al., 2007, 2008a, 2008b). Setting the linear factor too low (a smaller or easier resistance) will result in an under-estimation of the W' and the CP, whereas with a linear factor set too high (larger resistance) the W' will be overestimated without affecting the CP (Vanhatalo et al., 2008b).

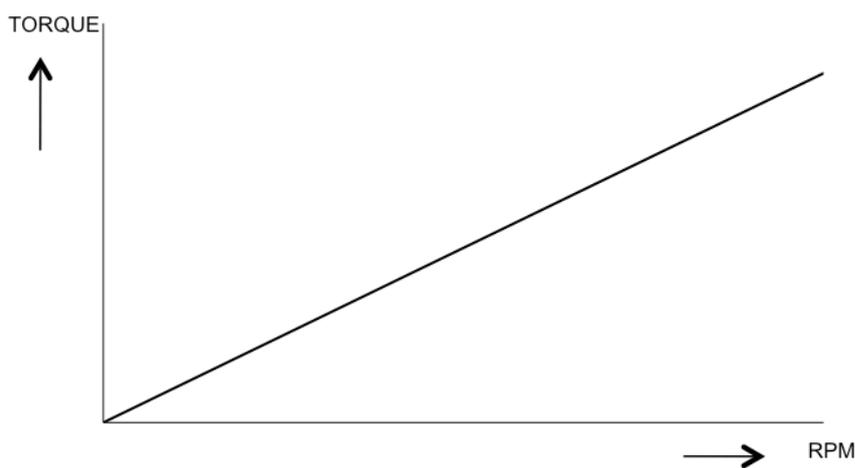


Figure 3.2. Linear relationship between torque & cadence in linear mode.

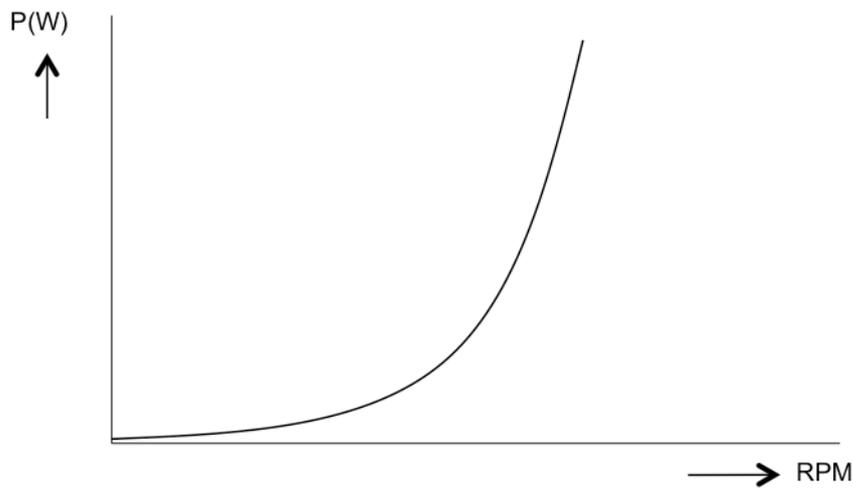


Figure 3.3. Exponential relationship between power & cadence in linear mode.

Participants are instructed to give a maximal effort at the beginning of the all-out portion of the test, attempting to attain a PPO as quickly as possible and maintain maximal effort throughout the test. Prior to the first 3-min all-out test, all participants were informed, in detail, about the expectations on them and the likely sensations that would be experienced throughout the test, including; initially a 'good feeling' of being powerful and 'on top of the gear' which quickly turns to a feeling of having 'set off too hard'; soon after, the effort becomes quite uncomfortable and ventilation will be noticeably very high; later on in the test the pedal cadence will feel very slow, as if cycling beneath mud or treacle. Following the initial explanation and completion of the first 3-min test, a shortened version of this brief was provided prior to all subsequent 3-min all-out tests for each participant. Throughout the all-out portion of the test participants received no indication of elapsed or remaining time yet received constant and consistent positive encouragement and instruction.

For each 3-min all-out test power output and pedal cadence from the ergometer was logged second-by-second using a custom-built piece of software which saved data to a text file, for later analysis within Microsoft Excel (Microsoft UK, Reading, UK). The 3-min all-out test data was plotted as power (y-axis) vs. time (x-axis) to inspect for signs of 'pacing' and to compute the end power (EP) and the work performed above end power (WEP). EP was taken as the average power output over the final 30 s of the all-out test. WEP was calculated as the work-time integral above EP. Where pacing was evident in the power profile of

the 3-min test, the data were excluded from any further analysis and the participant asked to repeat the test on a subsequent occasion. 'Pacing' within the 3-min test can take many forms, but typically results in a period of power output within the test which is noticeably lower than the EP (see Figure 3.4 p99 for examples). The power profile should resemble a rapid attainment of a PPO followed by a hyperbolic decline in power output over the next ~ 120 s at which point the power output becomes reasonably consistent second-by-second, effectively attaining a 'steady state' or asymptote.

A 3-min all-out test was accepted as successful (See Figure 3.4 p99) providing the following criteria were satisfied:

- 1) Power output was never lower than 10 W of the EP for more than ~ 5 consecutive seconds at any point.
- 2) Peak power and cadence were attained within the initial 10 s of the test and not matched or approached thereafter.
- 3) $\dot{V}O_2$ projected toward, and was maintained at 95 % $\dot{V}O_{2peak}$ throughout the 3-min test, despite the fall in power output to EP.

3.7. Measurement of Pulmonary Gas Exchange

During all exercise testing, pulmonary gas exchange was measured using a rapid response, online gas analyzer (Oxycon Pro, Jaeger, Hoechberg, Germany). Participants wore a nose clip and breathed through a low dead space (90 mL) mouthpiece and impeller turbine assembly (Triple V, Jaeger, Hoechberg, Germany). Ventilation volume and gas concentration were sampled continuously at a frequency of 100 Hz. Expired gas was sampled through a capillary line connected to the triple-V assembly with O_2 and CO_2 concentrations analysed by the paramagnetic and infrared analysers, respectively, of the Jaeger Oxycon Pro. Prior to every experimental session, the analysers were calibrated with gasses of known concentration and the impeller turbine calibrated for 'volume' with a 3 L syringe (Hans Rudolph, KS) which passed its known volume through the triple-V assembly and the mouthpiece connected in series. The volume and gas concentration signals were time-aligned by accounting for the delay in capillary gas transit and analyser rise time

relative to the volume signal. O_2 , CO_2 and V_E were calculated with standard formulae (Beaver, Wasserman, & Whipp, 1973) and displayed breath-by-breath within the manufacturers software.

3.8. Measurement of Blood Lactate Concentration

[Bla] was measured in ~ 20 μ L of capillary whole blood drawn from the finger tip into a heparinised Microvette (Sarstedt AG & Co., Numbrecht, Germany). Samples were stored at room temperature for a maximum of 20 min prior to analysis using an automated blood analyzer (YSI 2300, Yellow Springs, OH). The blood analyzer was calibrated hourly using the manufacturer's standard (YSI 2747) and its reliability checked regularly by technical staff with records showing the analyzer consistently returned results from known concentrations of lactate within 2 % of the expected values. Prior to blood samples being drawn, the selected fingertip was prepared with an alcohol swab (70 % isopropyl alcohol, Sterets, UK) prior to being pierced with a safety-lancet (Super, Sarstedt AG & Co., Numbrecht, Germany). The first drop of blood was wiped away on each occasion prior to collecting the sample for analysis.

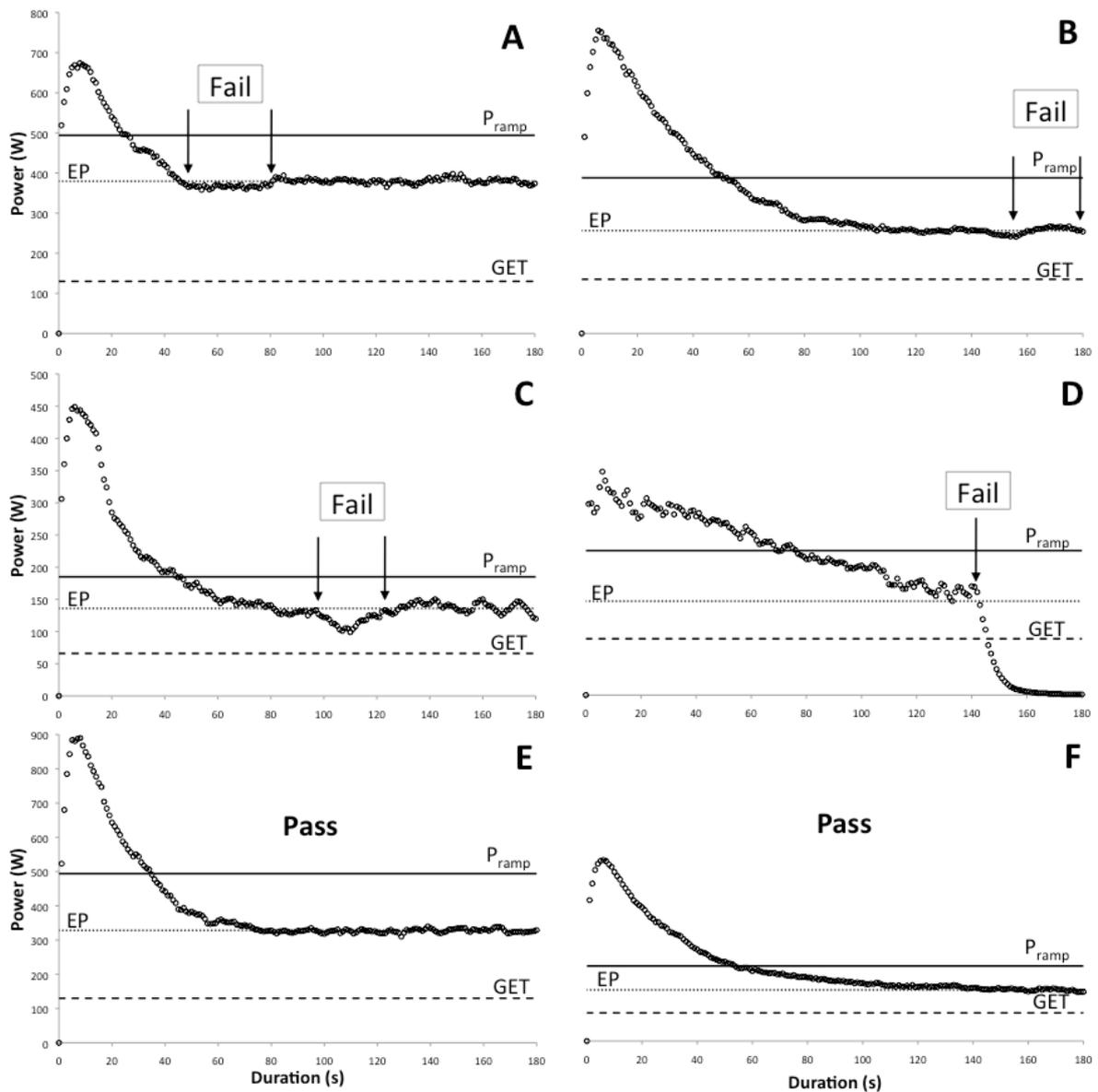


Figure 3.4. Correctly and incorrectly performed 3-min all-out tests.

The above panels provide individual examples of failed and correctly performed 3-min all-out tests. Bold horizontal lines represent the adjusted peak power attained at exhaustion during a ramp incremental exercise test (P_{ramp}). Large-dashed lines represent the power output corresponding to the GET. Finely-dashed lines represent the end power of the 3-min all-out test. Vertical arrows represent the portion of the test which rendered these examples 'failed' attempts; see below grid for explanation.

Panel(s)	Pass/Fail	Reason(s)
A	Fail	Power falls > 10 W below EP for more than 5 consecutive seconds. In this case, the fall in power is typical of the participant not providing a maximal effort during the emerging sensation(s) of physical discomfort.
B	Fail	Power falls > 10 W below EP for more than 5 consecutive seconds due to the presence of an 'end spurt' despite the absence of time feedback.
C	Fail	Power falls > 10 W below EP for more than 5 consecutive seconds. This example is indicative of a participant losing focus or concentration during the test, which can prevent a conscious maximal effort being given throughout.
D	Fail	Represents a participant failing to complete the 3-min duration, instead stopping maximal exercise sooner due to the sensations they were experiencing. The EP line was taken from a subsequent 3-min all-out test, performed correctly.
E & F	Pass	Well executed 3-min all-out tests. Peak power output attained within the initial 10 s. Smooth decline in power output thereafter, reaching a steady power output for the remaining duration of the test. Note that, in comparison to panels A & C, the EP of the participants in panels E & F fall very close to 50 %Δ; an additional (though not conclusive) indicator that the test had been conducted correctly. Furthermore, note the subtle difference in the power profile of the different participants in panels E & F; in panel E, a steady-state power is attained at ~ 80 s and maintained thereafter; in panel F the plateau in power occurs after ~ 120 s.

Chapter 4 – Influence of initial metabolic rate on the power-duration relationship for all-out exercise

4.1. Introduction

The asymptote of the hyperbolic power-duration relationship for high-intensity muscular exercise has been termed ‘critical power’ (CP), and is known to demarcate the boundary between heavy- and severe-intensity exercise (Jones et al., 2008; Poole et al., 1988). The CP therefore theoretically represents the maximum power output that may be maintained without inexorable increases in $\dot{V}O_2$, as well as blood [lactate] ([Bla]), inorganic phosphate (P_i), H^+ , and other metabolites which have been implicated in the fatigue process (Hill & Smith, 1999; Jones et al., 2008; Poole et al., 1988). The curvature constant of the P-D relationship for high-intensity exercise (W') is representative of a finite capacity of work, which retains its magnitude irrespective of the rate of expenditure (Fukuba et al., 2003; Poole et al., 1988).

The W' was originally thought to represent the energy derived from substrate-level phosphorylation derived from the intramuscular high-energy phosphate pool and anaerobic glycolysis, with an additional small contribution from myoglobin- and hemoglobin-bound oxygen stores (Hill, 1993; Miura et al., 1999; Monod & Scherrer, 1965; Moritani et al., 1981). However, rather than viewing W' as an expendable ‘anaerobic work capacity’, it has also been proposed that W' reflects the accumulation of fatiguing metabolites (i.e. P_i and H^+), that are associated with the process of muscular fatigue (Coats et al., 2003; Fukuba et al., 2003; Jones, Wilkerson, Burnley, & Koppo, 2003; Jones et al., 2008). Whilst its exact nature remains elusive, it is known that W' is only expended at work rates above CP (Ferguson et al., 2007; Fukuba et al., 2003; Jones et al., 2003; Monod & Scherrer, 1965).

The CP and W' have been conventionally determined by a protocol of 3 to 5 exhaustive bouts of severe-intensity exercise completed on different days (Monod & Scherrer, 1965; Moritani et al., 1981; Poole et al., 1988). However, the development of an ‘all-out cycling test’ to establish the CP and W' has

considerably expedited this process (Burnley et al., 2006a; Vanhatalo et al., 2007, 2008b). The all-out cycling test functions on the premise that 3-min of 'all-out' effort is sufficient to achieve a maximum value for W' , such that the power sustained over the final 30 s of the test (end power; EP) represents the CP with the work completed above the EP (work above end power; WEP) being equivalent to the W' (Vanhatalo et al., 2007, 2008a).

The all-out cycling test has previously only been commenced from an 'unloaded' baseline, where the individual cycles at the lowest power output available on the ergometer (usually 20 W), until instructed to give an all-out effort. Completing the all-out test with an immediate transition from an elevated metabolic baseline (i.e. at various power outputs > 'unloaded') affords the opportunity to test the validity of the CP concept and the robustness of the 3-min all-out test to an intervention designed to manipulate W' . The CP concept predicts that if the 3-min all-out test is completed from a metabolic rate that is below the EP, there should be no effect on the WEP estimate; however, transitions from metabolic rates above the EP should result in predictable reductions in the WEP parameter.

The purpose of the present investigation was therefore to determine if the all-out cycling test power profile is sensitive to a range of elevations in the metabolic rate immediately preceding the test. We hypothesized that for pre-test metabolic baselines below EP (i.e. in the moderate and heavy exercise intensity domains) there would be no change in the estimate of WEP, with predictable reductions in this parameter when the baseline metabolic rate was above EP (i.e. in the severe exercise intensity domain). We also hypothesized that differences in the pre-test metabolic baseline would not significantly alter the EP.

4.2. Methods

4.2.1. Subjects

Seven physically active male subjects (mean \pm S.D.: age 28 ± 10 years, body mass 74.2 ± 4.6 kg and height 1.77 ± 0.05 m) volunteered and gave written

consent to participate in this study which had been approved by the local research ethics committee.

4.2.2. Experimental design

Participants visited the laboratory on eight occasions over a three-week period with all tests separated by a minimum of 24 h. All exercise testing was conducted on an electromagnetically-braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands). On the first visit to the laboratory, the subjects completed a ramp incremental test to exhaustion for the determination of $\dot{V}O_{2peak}$ and the GET. On the second visit, the subjects completed a 3-min all-out familiarization trial, and on the third visit they completed a further 3-min all-out test which served as the control. Visits 4-7 involved further 3-min all-out tests initiated from moderate, heavy, and severe (completed for 2 and 4 min) intensity exercise presented in a randomized order. Visit 8 was a repeat of the 'control' visit to determine whether a training effect had occurred.

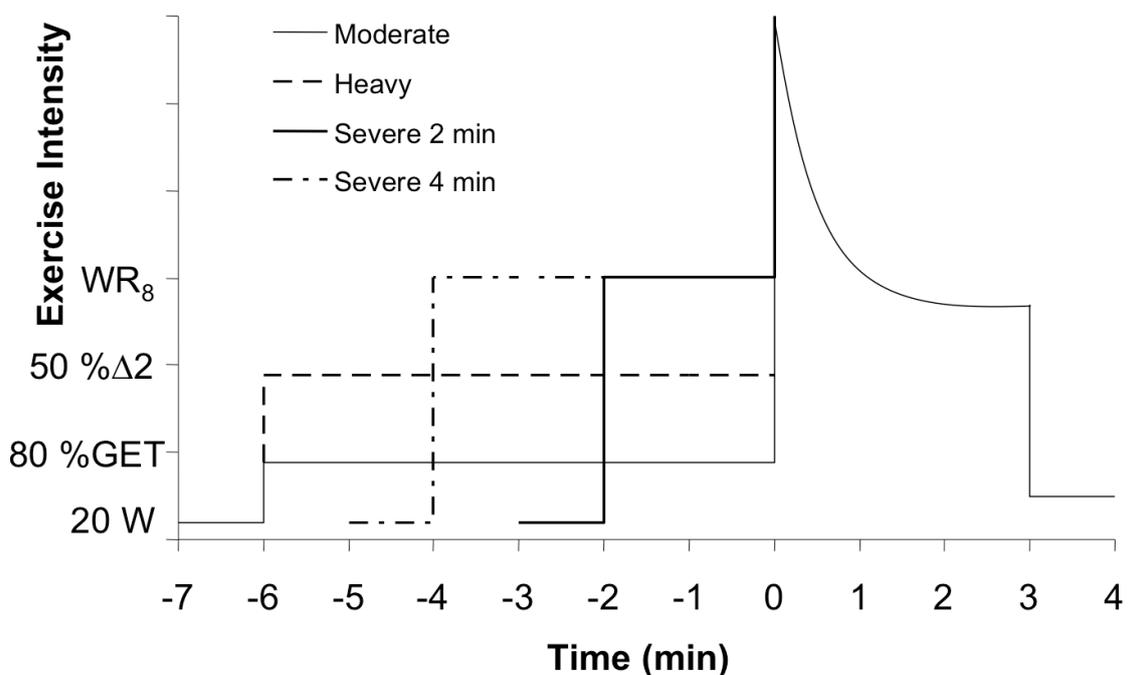


Figure 4.1. Schematic of experimental protocol.

Exercise protocol for moderate, heavy, severe 2-min and severe 4-min elevated baseline trials. Time zero represents the initiation of the 3-min all-out cycling test. See text for detailed description.

4.2.3. Determination of $\dot{V}O_{2peak}$ and GET

The ramp protocol consisted of 3-min of unloaded pedaling, followed by a ramp increase in power output of $30 \text{ W}\cdot\text{min}^{-1}$ until volitional exhaustion. Participants were asked to maintain their preferred cadence (all participants selected between 70-90 rpm) for as long as possible. The test was terminated when the cadence could no longer be maintained within 10 rpm of the preferred cadence for $> 5 \text{ s}$, despite strong verbal encouragement. Pulmonary gas exchange was measured breath-by-breath throughout all exercise tests (Oxycon Pro, Jaeger, Hoechberg, Germany). The volume transducer was calibrated before each test with a 3-litre calibration syringe (Hans Rudolph Kansas City, MO), and the analyzers were calibrated with gasses of known concentration. Gas exchange data were averaged into 10 s serial average bins for determination of the GET using the V-slope method (Beaver, Wasserman, & Whipp, 1986), and $\dot{V}O_{2peak}$ was defined as the highest 30 s serial average before the subject's voluntary termination of the test.

4.2.4. 3-min all-out cycling tests

For the familiarization and control tests, subjects completed 3-min of baseline cycling at their preferred cadence at 20 W, followed immediately by a 3-min all-out effort against a fixed resistance as described previously (Burnley et al., 2006a; Vanhatalo et al., 2007, 2008b). The resistance on the pedals during the 3-min all-out test was set using the linear mode of the ergometer so that the subject would attain a power output equivalent to 50 % of the difference between GET and $\dot{V}O_{2peak}$ (attained during the ramp test; $50 \% \Delta$) on reaching their preferred cadence (linear factor = $\text{power}/\text{preferred cadence}^2$). Within the final 5 s of the baseline period, subjects were instructed to increase cadence to ~ 110 -120 rpm. Participants were given a 5 s countdown to the start of the test, at which point a maximal effort was given for a duration of 3-min. Strong verbal encouragement was given throughout, but subjects were not informed of the elapsed time in order to prevent pacing. To ensure an all-out effort, subjects were instructed to attain their peak power as quickly as possible, and to maintain their cadence as high as possible until they were told to stop. The EP was calculated as the mean power output over the final 30 s of the test, the peak power and peak cadence as the highest 1 s value, and the WEP as the

power-time integral above EP using commercially available software (Microsoft Excel, 2007). The $\dot{V}O_{2peak}$ during the 3-min all-out test was defined as the highest 15 s serial mean recorded during the bout.

Four of the 3-min all-out tests were initiated from an elevated metabolic baseline condition (Figure 4.1 p103). The different intensities of the pre-test metabolic rate were: (i) moderate (6 min at a power output equivalent to 80 %GET); (ii) heavy (6 min at a power output equivalent to 50 % of the difference between the GET and EP from the control 3-min test (50 % Δ 2)); (iii) severe intensity for 2 min (S2), i.e. 2 min at a power output calculated to elicit exhaustion at 8 min (WR₈; calculated based on data from the 3-min control test); and (iv) severe intensity for 4 min (4 min at WR₈; S4). All elevated baseline bouts were preceded by 3-min of unloaded pedaling (20 W). The equation used to calculate the power output expected to lead to exhaustion in 8 min was as follows:

$$WR_8 = (WEP/T_{lim}) + EP \quad [4.1]$$

where: WR₈ is the target power output, T_{lim} is the time to exhaustion (i.e. 480s), EP is the CP and WEP is the finite work capacity above CP in joules. Eight minutes at WR₈ will result in complete depletion of WEP; therefore 2 and 4 minutes of exercise at WR₈ will result in a 25 and 50 % reduction in WEP, respectively. The above transformation of the original CP equation was originally proposed by Whipp et al. (1982).

A capillary blood sample was taken at rest and immediately pre- and post-3-min all-out test for determination of [Bla] (YSI Stat 2300, Yellow Springs, OH).

4.2.5. Statistical analysis

Differences in WEP, EP, peak power output (PPO), total work done and pre 3-min test [Bla] between trials were analyzed using one-way ANOVAs with repeated measures. Where there was a significant main effect, individual differences were investigated by post hoc paired-samples t-tests with a Bonferroni correction. The values for EP and WEP from the pre- and post-control 3-min tests were compared via paired-samples t-tests. Pearson

product-moment correlations were used to assess the relationship between WEP and PPO. Significance was accepted at $P < 0.05$. Results are reported as means \pm SD.

4.3. Results

The subjects' $\dot{V}O_{2peak}$ measured in the ramp incremental test was 4.19 ± 0.82 $L \cdot min^{-1}$ with the GET occurring at 1.87 ± 0.41 $L \cdot min^{-1}$ which corresponded to 392 ± 68 W and 111 ± 24 W respectively. The power output at 50 % Δ was 252 ± 44 W and the power output for moderate, heavy and S2/S4 was 89 ± 19 , 188 ± 44 and 301 ± 67 W, respectively. There were no differences in any of the 3-min test parameters between the pre-control and the post-control conditions indicating that there was no appreciable training effect over the course of the study. The mean pre-post difference in the EP and WEP were 8 ± 32 W and -1.4 ± 2.8 kJ respectively.

Table 4.1. Mean (\pm SD) 3-min all-out parameters from trial conditions.

	Control	Moderate	Heavy	Severe 2 min	Severe 4 min
EP (W)	279 \pm 62	275 \pm 52	286 \pm 66	274 \pm 55	273 \pm 65
WEP (kJ)	16.3 \pm 2.2	17.2 \pm 2.4	15.6 \pm 2.3	11.5 \pm 2.5 ^a	8.9 \pm 2.2 ^a
PPO (W)	791 \pm 104	754 \pm 96	739 \pm 128	605 \pm 101 ^a	549 \pm 102 ^a
Work done (kJ)	66.4 \pm 9.9	66.7 \pm 9.2	67.0 \pm 10.5	60.9 \pm 9.0 ^a	58.1 \pm 10.6 ^b
Peak cadence (RPM)	145 \pm 7	141 \pm 7	140 \pm 10	126 \pm 6 ^a	120 \pm 8 ^a
$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	3.92 \pm 0.67	3.90 \pm 0.64	4.11 \pm 0.72	4.03 \pm 0.72	4.11 \pm 0.78
Pre 3-min $\dot{V}O_2$ ($L \cdot min^{-1}$)	0.99 \pm 0.14 ^c	1.59 \pm 0.26 ^c	2.69 \pm 0.54 ^c	3.5 \pm 0.84 ^c	3.91 \pm 0.83 ^c
Pre 3-min as % $\dot{V}O_{2peak}$	20 \pm 9 ^d	38 \pm 4 ^d	64 \pm 6 ^c	83 \pm 4 ^c	93 \pm 3 ^c
Pre 3-min Bla (mM)	1.1 \pm 0.5	1.3 \pm 0.5	1.8 \pm 0.7	1.7 \pm 0.5	3.7 \pm 0.9 ^e

^a Significantly different to control, moderate and heavy trials ($P < 0.05$)

^b Significantly different to moderate and heavy trials ($P < 0.01$)

^c All trials different from one another ($P < 0.05$)

^d Significantly different to heavy, severe 2-min and severe 4-min trials ($P < 0.05$)

^e Significantly different to control and moderate trials ($P < 0.05$)

There were no differences in the EP across all conditions (Table 4.1 p106). The WEP was significantly affected by the elevated metabolic rate only when the 'baseline' was in the severe exercise intensity domain. Specifically, WEP for S2 and S4 were both significantly reduced compared with the control, moderate, and heavy conditions ($P < 0.05$), but there was no difference between WEP for S2 and S4 ($P > 0.05$; Table 4.1 p106). The measured reduction in WEP following both S2 and S4 (33 ± 10 and 48 ± 12 %, respectively) was not significantly different from the reductions in WEP that were expected from that calculated (i.e., 25 and 50 % respectively).

The total work done during the 3-min test was significantly reduced in S2 compared to the control, moderate, and heavy conditions ($P < 0.05$; Table 4.1 p106), with significant reductions also noted for S4 vs. moderate and heavy ($P < 0.05$). Both PPO and peak cadence were significantly reduced in S2 and S4 compared to control, moderate, and heavy (Table 4.1 p106). The group mean power profiles for all conditions are shown in Figure 4.2 p108.

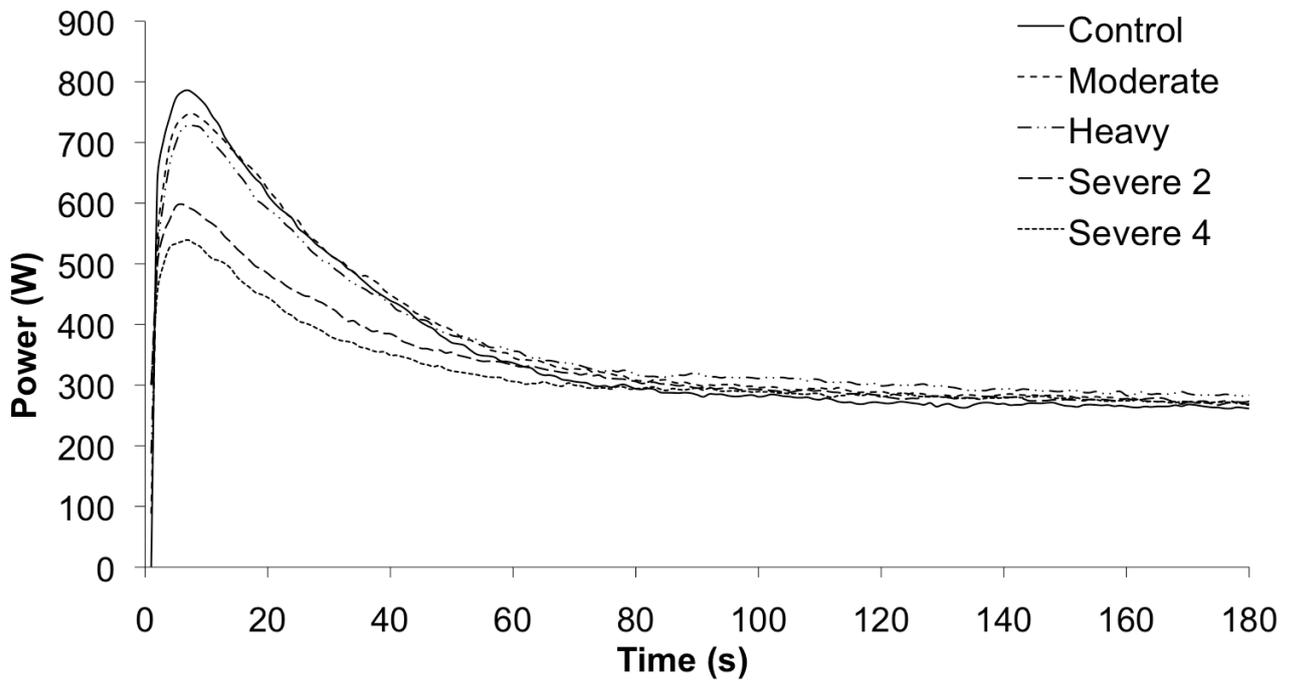


Figure 4.2. Mean 3-min all-out test power profile.

Group mean power profiles during each 3-min all-out cycling test following each different preceding baseline. Note the consistent end test power across all of the trials, and the reduced power output over the initial 60 to 90 s of the test when the baseline condition was in the severe exercise intensity domain.

The $\dot{V}O_{2peak}$ measured during each 3-min all-out test preceded by an elevated baseline was not different from the $\dot{V}O_{2peak}$ measured during the ramp incremental test (Table 4.1 p106). The group mean $\dot{V}O_2$ responses are presented in Figure 4.3 p109.

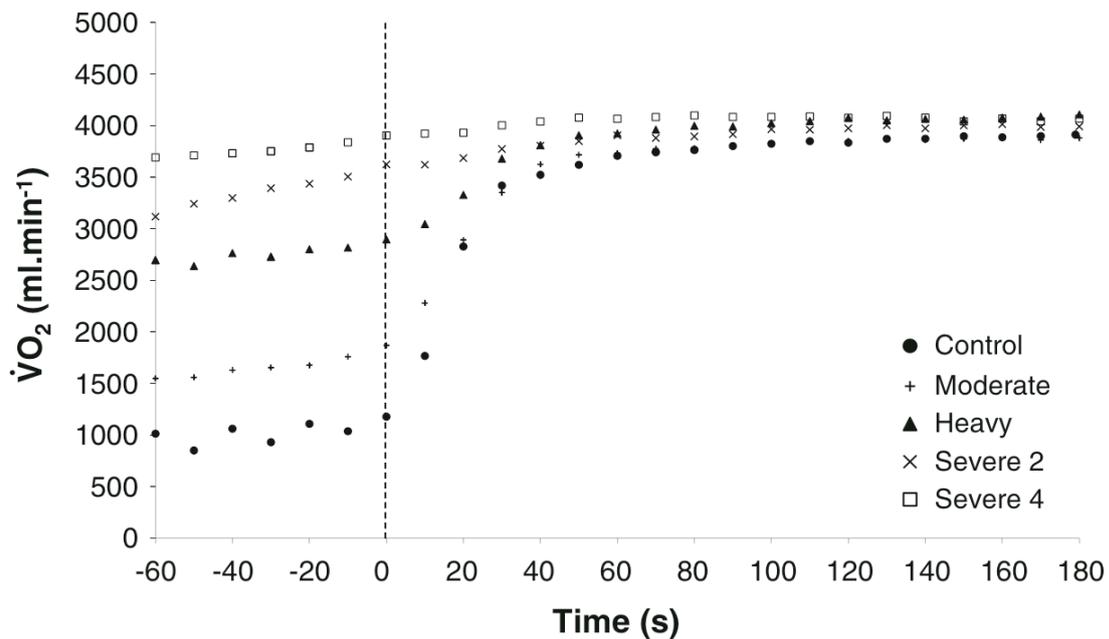


Figure 4.3. Mean $\dot{V}O_2$ response under each condition.

The group mean $\dot{V}O_2$ response profiles during the 3-min all-out test initiated from various baseline conditions.

4.5. Discussion

The principal finding of this investigation was that the WEP was significantly and predictably reduced when the all-out cycling test was initiated from exercise intensities above EP. In contrast, when the all-out test was initiated from exercise intensities below the EP, the WEP was not different from that determined in the control (unloaded baseline) condition. The initial metabolic rate had no effect on the EP when the test was initiated from 20 W, moderate, heavy or severe intensity exercise. These findings are consistent with our hypotheses and indicate that: 1) WEP is only appreciably 'accessed' at power outputs > EP; and 2) the EP determined in the all-out test is not altered by the performance of exercise > EP, which is associated with considerable muscle metabolic perturbation (Jones et al., 2008).

The power profiles during the 3-min all-out test were markedly different when the test was initiated from a baseline power above, compared to below, an individual's EP. The significantly lower PPO and lower power output over the first ~90 s of the S2 and S4 tests gave rise to a significantly reduced WEP when

compared to tests initiated from below an individual's EP (i.e. control, moderate and heavy; Figure 4.2 p108). These data are in agreement with Heubert et al. (2005), who demonstrated that the W' was significantly reduced when the conventional prediction trials were initiated from an all-out sprint of 7 s compared to when initiated from rest. The systematic reduction in WEP following 2 and 4 min of severe exercise is also in agreement with Fukuba et al. (2003) who concluded that the W' is accessed at an intensity-dependent manner at power outputs above CP. This is the first study to demonstrate that the WEP measured in the novel all-out protocol is similarly sensitive to the initial metabolic rate and extends previous findings by placing the pre-test power outputs within distinct exercise intensity domains.

The exact physiological underpinning of W' remains elusive. It was traditionally thought to represent a finite energy store associated with PCr, glycogen and O_2 bound to myoglobin (Miura et al., 1999; Miura et al., 2000; Moritani et al., 1981). However, it is becoming more widely accepted that the magnitude of W' might be determined by the accumulation of fatigue-inducing metabolites, such as H^+ and P_i and extracellular K^+ (Fitts, 1994) to some critical limit, while intramuscular PCr and glycogen are simultaneously depleted (Jones et al., 2010). In the present study, the moderate exercise intensity condition would have had little impact upon muscle PCr and glycogen stores and the accumulation of fatiguing metabolites; therefore it was not surprising that this condition did not significantly influence WEP. Heavy intensity exercise may not have an appreciable impact upon muscle [PCr], but 6 min duration may be sufficient to reduce muscle glycogen stores (Krustrup, Soderlund, Mohr, Gonzalez-Alonso, & Bangsbo, 2004). It is, however, unlikely that the 3-min all-out test has the requisite resolution to detect very small reductions in WEP subsequent to a modest reduction in muscle glycogen stores in the heavy intensity condition. This point may be academic, considering that recent studies have questioned the importance of anaerobic glycolysis to the W' (Ferguson et al., 2007; Vanhatalo & Jones, 2009b). Vanhatalo and Jones (2009b) recently demonstrated that the WEP determined via the 3-min all-out test 15 min after 30 s of maximal sprinting was not different from the WEP determined in a control 'no prior exercise' condition. The 30 s of maximal sprinting would have been expected to elicit a substantial reduction in muscle

glycogen (Bogdanis et al., 1995; Cheetham, Boobis, Brooks, & Williams, 1986). These results suggest that the rate of intramuscular PCr depletion may be more important than glycogen availability in determining the WEP. The data of Vanhatalo and Jones (2009b) and that of the present study indicate that the 3-min all-out test has the requisite sensitivity to detect reductions in WEP elicited by prior supra-EP exercise. Further insight into the relative contribution of the accumulation of fatiguing metabolites and reductions in PCr (and perhaps glycogen) to the reductions in WEP occurring in S2 and S4 cannot be derived from the current data.

In the conditions when the WEP was partially reduced prior to the onset of the 3-min test (i.e. S2 and S4 conditions), the PPO was significantly lower compared to the other conditions, despite there presumably being W'/WEP accessible to achieve the same PPO value recorded in the control condition. The power profiles followed the same pattern regardless of the metabolic rate at the test onset: after attainment of the PPO within ~5 s, the power output fell progressively, reaching a plateau after ~120-150 s which was then maintained for the remainder of the test (Figure 4.2 p108). The reduction in PPO observed in the S2 and S4 trials may be a consequence of impaired muscle function at the onset of the 3-min test due to the accumulation of fatigue-related metabolites during the preceding bout of severe exercise (Jones et al., 2008). This finding is in contrast to the earlier notion that W' represents a fixed anaerobic energy store, which is not rate-limited (Miura et al., 1999; Monod & Scherrer, 1965; Moritani et al., 1981). According to the 3-parameter CP model (Morton 1996) the maximum instantaneous power achievable is inversely proportional to the 'remaining energy store'. The behavior of the PPO in the present study may therefore be seen to reflect this 'linear control feedback' on W'/WEP (Morton, 2006).

That EP and $\dot{V}O_{2peak}$ were not significantly different between any of the conditions is consistent with previous studies which have manipulated the pre-exercise conditions via prior heavy (Jones et al., 2003), severe (Ferguson et al., 2007), and sprint exercise (Heubert et al., 2005). The S2 and S4 conditions, where the WEP was reduced by up to 50 % prior to the all-out test, indicate that the prior depletion of WEP does not have a discernible effect on the EP. The

similarity of the EP across the different trials may perhaps be explained by fatigue of the different muscle fibre type populations. The all-out nature of the 3-min test mandates that all available muscle fibres will be recruited from the onset of the test, with the progressive decline in power output over the first 120 s being reflective of the sequential fatiguing of the fibres, such that the population of fibres remaining active to meet the demand for muscle force production in the final 60 s of the test are likely to be the most fatigue resistant type I fibres (McCartney, Heigenhauser, & Jones, 1983; Sargeant, 1994). The high intensity nature of S2 and S4 will have mandated a greater contribution from the less fatigue resistant type II fibre populations, thereby limiting their ability to contribute towards the power output measured over the early stages of the 3-min all-out test (first 60-120 s), where the vast majority of the WEP is 'utilised'. Thus differences in fibre-specific contribution to power production during the 3-min all-out test following different metabolic baselines might explain the changes in WEP and the lack of change in EP. In this respect, the data from this study are consistent with those of Vanhatalo and Jones (2009b), who demonstrated a significant reduction in PPO and WEP when the 3-min all-out test was initiated 2 min after a 30 s period of maximal sprint exercise but not after 15 min recovery when type II fibres might have restored their capacity for force production (Bogdanis et al., 1995).

In conclusion, the present study has shown that when the 3-min all-out test is initiated from elevated metabolic baselines below the EP there is no impact upon the WEP. However, when the test is initiated from baselines above the EP, there is a predictable reduction in the WEP. Despite significant effects on WEP, the EP was not significantly altered when the 3-min all-out test was initiated from a power output above or below the EP. The P-D parameters estimated in the novel all-out protocol appear to respond to the manipulation of the initial metabolic rate in a similar manner to the CP and W' established using the conventional prediction trial method. These findings are in accordance with the fundamental principles of the P-D relationship for severe-intensity exercise and support the notion that CP is independent of the factors which have a deleterious impact on the W'.

Perspective 1

The 3-min all-out test parameters (EP & WEP) are robust to the test being initiated from an elevated metabolic baseline at intensities below the EP(/CP). The EP parameter is robust even when the 3-min test is performed from a severe-intensity 'baseline'. However, and in agreement with the CP concept, the WEP is reduced when the test is preceded by severe-intensity exercise, which by its definition will 'consume' a quantifiable portion of the available W' . The 3-min test appears sensitive enough to detect the magnitude of W' remaining following a period of severe-intensity exercise. As such, it would be expected that the all-out test would be sensitive to other interventions that should theoretically reduce the W' , for example, depleting the muscle fibre glycogen store.

Chapter 5 – Effect of type I and type II muscle fibre-specific glycogen depletion on ‘critical power’ and W' determined using the 3-min all-out cycling test

5.1. Introduction

Endurance sport performances involve exercise of a heavy- and severe-intensity, both of which require the recruitment of type II muscle fibres (Beltman et al., 2004; Hultman, 1995; Wilkerson & Jones, 2006) and thus the utilisation of muscle glycogen. The rate of glycogen utilisation is linearly proportional to exercise intensity (van Loon et al., 2001). When severe intensity exercise is initiated from a glycogen depleted state, T_{lim} is reduced (Maughan & Poole, 1981) but as the severity of the workload reduces, little difference is observed in the tolerable duration between the depleted and non-depleted states, with muscle glycogen depletion resulting in a reduction in W' without affecting the CP parameter (Miura et al., 2000).

Withers et al. (1991) reported that for sprint cycle exercise of durations up to 90 s, muscle glycogen contributed little toward muscle metabolism, with Phosphocreatine (PCr) being the major contributor (PCr:Glycogen ratio of ~ 7:3 contribution) to the muscular work. This would suggest that sprint cycling exercise is not affected by glycogen content despite the apparent contribution of glycogen to the anaerobic energy reserve utilised at exercise intensities above the CP (Maughan & Poole, 1981). Indeed, when exercise is maintained just above the intensity of $\dot{V}O_{2max}$ (104 %), muscle glycogen availability appears to markedly affect severe-intensity exercise tolerance. Under habitual dietary conditions, severe-intensity exercise was sustained for 4.87 ± 1.07 min. following an exhaustive glycogen depletion exercise bout (~ 75 % $\dot{V}O_{2max}$) and three days of a low carbohydrate diet (3 % energy from carbohydrates; 17 MJ daily intake) the severe-intensity exercise bout was tolerated for 3.32 ± 0.93 min (~ 34 % reduction in T_{lim}). Following a further 3 days of a high carbohydrate diet (84 % energy from carbohydrates; 10 MJ daily intake) the severe-intensity exercise test was repeated with T_{lim} averaging 6.65 ± 1.39 min (~ 35 % increase

in T_{lim} ; (Maughan & Poole, 1981)). While this evidence does not pertain to whether it is the CP or W' parameter which is reduced/enhanced with diminished/elevated muscle glycogen content, it does provide quite clear evidence that muscle glycogen availability plays a considerable role in determining severe-intensity exercise tolerance.

The 3-min all-out cycling test is a 180 s maximal effort on a cycle ergometer which provides estimates of CP and W' in a single test. The end power (EP; average power output over the final 30 s of the test) closely approximates CP with the power-time integral above EP, known as work performed above end power (WEP) approximating the W' (Burnley et al., 2006a; Vanhatalo et al., 2007). Due to the nature of the test, being effectively a prolonged sprint, it presumably maximally challenges first the anaerobic system and the type IIb and IIx fibres before relying on the un-fatigued type IIa fibres and fully recruited type I, aerobic, fibres to produce power output (Vanhatalo et al., 2011). Inducing glycogen depletion to the two distinct muscle fibre pools (Type II or Type I) prior to the 3-min test should theoretically result in differing power profiles. For example, targeted glycogen depletion of type II muscle fibres would presumably reduce the WEP parameter by limiting the volume of work which may be performed within the severe-intensity domain; whereas, glycogen depletion of type I muscle fibres should not affect the WEP but may slightly lower the EP parameter if glycogen is a contributor to the magnitude of the CP or the upper limit of the heavy-intensity domain.

The purpose of this study was to investigate whether glycogen is a significant determinant of the W' by selectively depleting glycogen in type I and type II muscle fibres prior to undertaking a 3-min all-out cycling test. We hypothesised that should glycogen be a major determinant of the W' , we would observe a substantially reduced WEP following the depletion of type II muscle fibres with no decrement in EP; whereas glycogen depletion of the type I muscle fibres would not compromise the WEP but may result in a slight reduction in EP.

5.2. Methods

5.2.1. Determination of $\dot{V}O_{2peak}$ and GET

Eight physically active males (Age 23 ± 4 yr; Stature 1.79 ± 0.07 m; Mass 78.9 ± 7.3 kg; $\dot{V}O_{2max}$ 4.2 ± 0.4 l.min⁻¹) volunteered, providing written informed consent, to participate in this study which was approved by the local research ethics committee. Participants visited the laboratory on a minimum of six occasions having refrained from strenuous exercise, alcohol and caffeine consumption for the 24, 48 and 3 hours prior, respectively. The initial visit enabled the determination of $\dot{V}O_{2max}$ and the GET using a 30 W.min⁻¹ incremental ramp exercise protocol on an electromagnetically-braked cycle ergometer (Lode Excalibur Sport, Lode, Groningen, Netherlands). Participants were asked to maintain their preferred cadence for the duration of the test with exhaustion being defined as the point at which cadence could no longer be maintained within ± 10 rpm of the preferred value, despite strong verbal encouragement. P_{ramp} was recorded as the highest power achieved before cadence fell out with 10 rpm of the preferred value minus two-thirds of the ramp rate (20 W; (Whipp, Ward, Lamarra, Davis, & Wasserman, 1982b)). The seat height and handlebar positioning were adjusted prior to the test to suit the preference of each participant. These preferences were recorded and replicated for all subsequent testing.

The GET was determined by at least two independent researchers via the V-slope method described previously (Beaver et al., 1986) as the first point at which $\dot{V}O_2$ showed a marked rise without a simultaneous rise in $\dot{V}CO_2$.

5.2.2. Estimation of critical power and W'

On the second visit, participants reported to the laboratory in the morning in a rested, and fasted (≥ 10 hour overnight fast) state to perform a 3-min all-out cycling test, preceded by 3 minutes of unloaded (~ 20 W) cycling at their preferred cadence. During the final 5 s of unloaded cycling, participants were asked to increase their cadence to 100 rpm before sprinting maximally for 3 minutes. Strong verbal encouragement was given throughout each 3-min all-out

test; participants had no indication of elapsed or remaining time to help prevent 'pacing' of their effort. The resistance, against which each participant sprinted was set using the linear factor (LF) function of the ergometer where;

$$\text{Power} = \text{LF} \times (\text{Cadence}^2) \quad [5.1]$$

The linear factor was adjusted so that at the preferred cadence of each participant, a power output equivalent to 50 % of the difference between the GET and P_{ramp} (50 % Δ) from the initial ramp exercise test would be produced.

Where there were no signs of 'pacing' (i.e. a smooth hyperbolic fall in power output, attaining a plateau over the final portion of the 3-min test with no marked increases or decreases in power output), the average power output over the final 30 s of the test was taken as EP with work completed above EP providing WEP. If 'pacing' was evident, the test (and thus the preceding glycogen depleting bout) was repeated on a subsequent visit.

5.2.3. *Glycogen depletion protocols*

The third and fifth visits were conducted in a counterbalanced order and were designed to target glycogen depletion in specific muscle fibre types. The methods employed were based on those of Carter et al. (2004). Participants reported to the laboratory in the late afternoon (15:00 – 18:30) to undergo either the type I muscle fibre depletion condition, requiring participants to cycle for 3 hours at 30 % P_{ramp} at 60 rpm; or the type II muscle fibre glycogen depletion condition. This required participants to complete ten, 1-min bouts of cycling at 120 % P_{ramp} , each followed by 1 min active recovery at 50 W and 4 minutes of passive rest. Each 1 min exercise bout and the active recovery were performed at the preferred cadence from the ramp incremental test.

The following morning participants reported to the laboratory, prior to the consumption of any food or drink (other than water), to perform a 3-min all-out cycling test identical to that detailed above. The glycogen depleting bouts were separated by at least one week and no more than four weeks.

5.2.4. Pulmonary gas analysis

Pulmonary gas was collected continuously, breath-by-breath (Jaeger Oxycon Pro, Jaeger, Germany) throughout the ramp-incremental exercise test and all 3-min all-out cycling tests. During the glycogen depletion conditions, pulmonary gas was collected intermittently. During the type I depletion condition, participants wore the mouthpiece and nose clip for the first 13 minutes and the final 10 minutes of each 30 min period thereafter. During the type II depletion condition pulmonary gas was collected for 3 min prior to, during and for 4 min following bouts 1, 5 and 10. Participants breathed through a low-dead space mouthpiece connected to a turbine housing a gas sample line to detect the fraction of O₂ and CO₂ in expired breath. A nose clip was worn simultaneously to ensure all expired air travelled through the turbine. The online gas analysis system was calibrated prior to each testing occasion against gasses of known concentration and a 3 L syringe (Hanz Rudolph, KS).

5.2.5. Blood lactate & blood glucose analysis

[Bla] and blood glucose concentration ([Bglu]) were analysed simultaneously using an automated combined Bla and Bglu analyser (YSI 2300 Stat, YSI, Yellow Springs, USA) from whole blood samples drawn from a finger-prick. Samples were taken at rest, immediately post and 5, 10 and 15 min post each 3-min all-out cycling test. During the type I glycogen depletion bouts, samples were taken at rest, and during the final min of each 10-min pulmonary gas collection period (8 samples). During the type II depletion condition samples were collected during the final min prior to, immediately post and at 4 min post bouts 1, 5 and 10.

5.2.6. Dietary manipulation

Participants were asked to record the food consumed and the time at which it was consumed on the day prior to and the day of their first glycogen depletion condition. Following completion of the glycogen depletion exercise bout participants were required to abstain from the consumption of foods containing moderate – high carbohydrate until the completion of the 3-min all-out test the following morning. The food choices issued to participants included lean meat

and fish, eggs, onion, mushroom, green vegetables and other vegetables low ($\leq 5\text{g}\cdot 100\text{g}^{-1}$) in carbohydrate content. These options were issued based on a nutrition database search (www.nutritiondata.com) for vegetables sorted in ascending total carbohydrate content. Commonly available vegetables within the local area, which appeared toward the top of the search results (lowest carbohydrate content) were suggested to participants. Due to the prolonged nature of the type I depleting trial, it was deemed necessary to permit participants to have an evening meal rather than ask them to fast overnight; as this was the case for one condition, the same meal was necessary for the type II depletion trial also for experimental standardisation. Participants were required to record their food consumption following the depletion bout and the recorded diet was replicated prior to and the evening of the second glycogen depleting bout.

5.2.7. Statistical analysis

Results for EP, WEP, Work Done, PPO, Peak Cadence, and [Bla] at each time point were analysed using a one-way repeated measures ANOVA. Where a significant main effect was reported, multiple paired samples t-tests were conducted with a Bonferroni correction to the alpha level of 0.05.

5.3. Results

$\dot{V}O_{2\text{max}}$ measured during the ramp incremental test reached $4.2 \pm 0.4 \text{ l}\cdot\text{min}^{-1}$ with the GET occurring at $1.7 \pm 0.3 \text{ L}\cdot\text{min}^{-1}$ corresponding to $363 \pm 45 \text{ W}$ and $114 \pm 22 \text{ W}$ respectively. The EP obtained from the Control 3-min test was $225 \pm 44 \text{ W}$ with WEP being $21.1 \pm 2.2 \text{ kJ}$. Total work done throughout the 3-min test equated to $61.5 \pm 8.7 \text{ kJ}$. Mean results for all 3-min test parameters are presented in Table 5.1 p120, with mean power profiles displayed in Figure 5.3 p122. The power output at $30 \%P_{\text{ramp}}$ was $105 \pm 12 \text{ W}$ which corresponded to $93 \pm 11 \% \text{GET}$ with the power output at $120 \%P_{\text{ramp}}$ being $417 \pm 48 \text{ W}$. Following the type II fibre depletion protocol, there were no significant differences observed in any 3-min test parameters when compared to both control and type I conditions (Table 5.1 p120). Similarly, following the type I

fibre depletion protocol, no significant differences were observed in any of the 3-min all-out test output parameters but [Bla] was significantly reduced immediately, 5-min and 15-min post 3-min test when compared to the control condition ($P < 0.04$; see Figure 5.1 p120). There were also no differences in the group mean $\dot{V}O_2$ over the final 30 s of the 3-min all-out test between conditions (Figure 5.4 p123).

Table 5.1. Mean (\pm SD) 3-min test parameters under each condition. Control (normal glycogen), type I depletion (glycogen depletion of type I muscle fibres) and type II depletion (glycogen depletion of type II muscle fibres).

	Control	Type I Depletion	Type II Depletion
EP (W)	225 \pm 44	226 \pm 55	220 \pm 46
WEP (kJ)	21.1 \pm 2.2	19.2 \pm 4.8	20.8 \pm 3.4
Work Done (kJ)	61.5 \pm 8.7	59.8 \pm 10.8	60.4 \pm 9.7
PPO (W)	783 \pm 99	737 \pm 82	783 \pm 72
Peak Cadence (rpm)	151 \pm 10	147 \pm 12	151 \pm 8

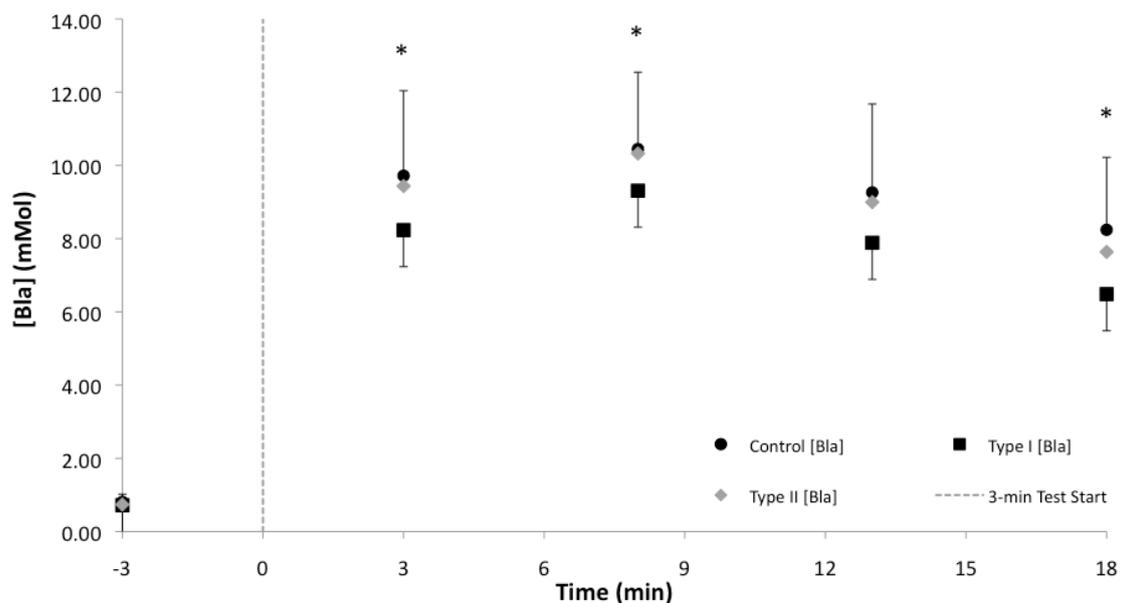


Figure 5.1. Post 3-min test [Bla] response.

[Bla] over the 3-min all-out test under each of the three trial conditions; control (closed circles), type I glycogen depletion (closed squares) and type II glycogen depletion (closed grey triangles). * denotes a significant difference between control and type I depletion conditions ($P < 0.04$).

Oxygen consumption showed a tendency to rise over the 3 hr, type I depletion trial, noticeably so from ~ 90 min onward where a group mean increase of 178 ml·min⁻¹ was observed.

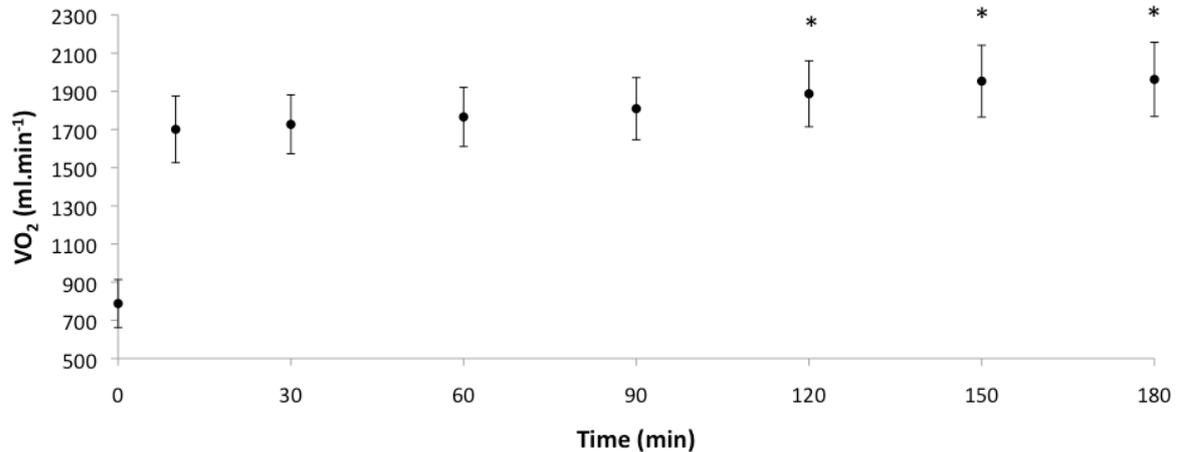


Figure 5.2. Type I depletion protocol mean $\dot{V}O_2$ response.

$\dot{V}O_2$ over 3-hr type I depletion trial. Each data point represents the group mean for the 10-minute sample point prior to the time point indicated on the horizontal axis. * represents a significant difference to $\dot{V}O_2$ at 60 min ($P < 0.004$).

During the type II depletion protocol, peak $\dot{V}O_2$ over intervals 1, 5 and 10 were 3.24 ± 0.40 , 3.58 ± 0.34 and 3.62 ± 0.32 ml·min⁻¹ respectively with $\dot{V}O_2$ from intervals 5 and 10 being significantly different to $\dot{V}O_2$ from interval 1 ($P < 0.001$). $\dot{V}O_2$ from intervals 5 and 10 did not differ ($P > 0.3$). Similarly, [Bla] post intervals 5 and 10 (7.41 ± 2.41 and 9.44 ± 1.49 mMol/L respectively) were significantly different to [Bla] post interval 1 (3.24 ± 0.48 mMol, $P < 0.007$). However, [Bla] post interval 10 was significantly different to [Bla] post interval 5 also ($P < 0.05$).

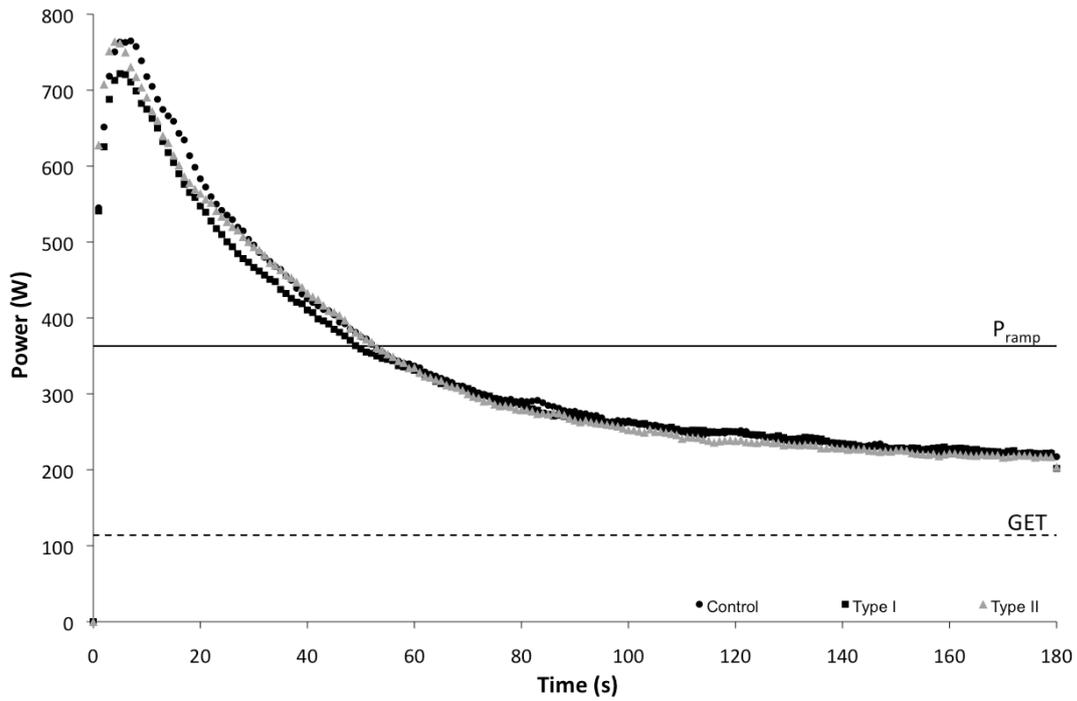


Figure 5.3. Mean 3-min test power profiles.

Mean 3-min all-out power profiles from control (closed circles), type I glycogen depletion (closed squares) and type II glycogen depletion (closed grey triangles) conditions. Standard error bars are omitted to enable for clearer presentation of the data. Please refer to Table 5.1 p120 for mean \pm SD values for the above 3-min all-out test.

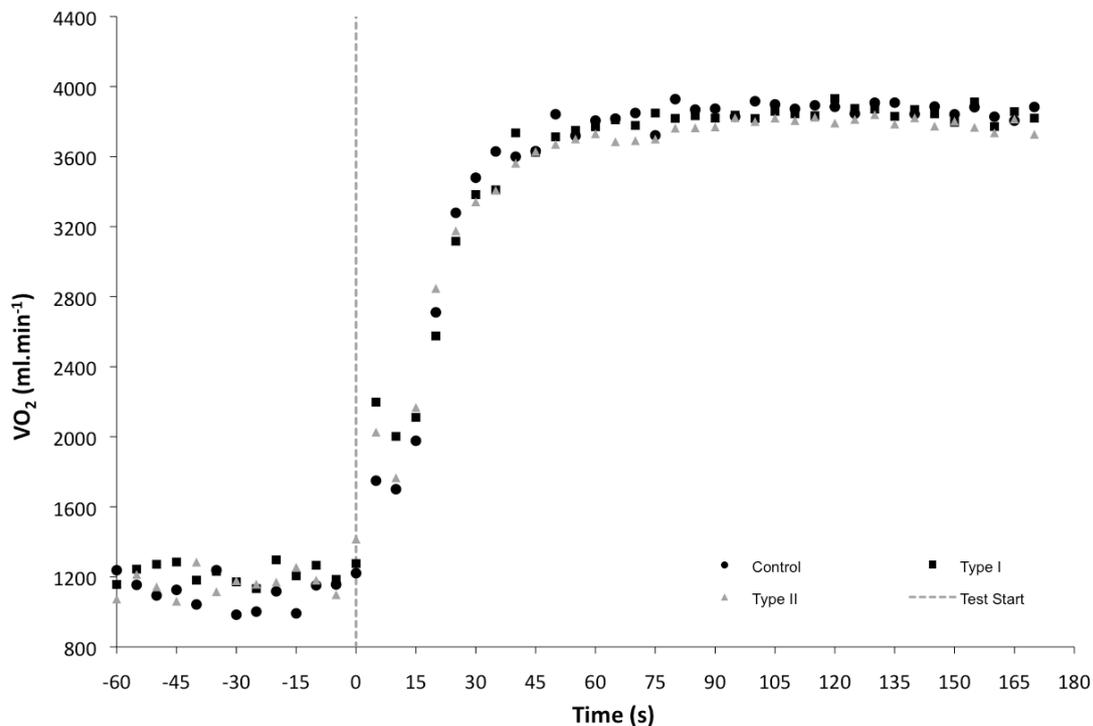


Figure 5.4. Mean 3-min test $\dot{V}O_2$ profiles.

Group mean $\dot{V}O_2$ during the 3-min all-out test in each muscle glycogen condition; control (closed circles), type I glycogen depletion (closed squares) and type II glycogen depletion (closed grey triangles). There is no discernable difference in the $\dot{V}O_2$ responses during the 3-min test despite manipulations in the muscle glycogen levels of both type I and type II muscle fibres.

5.4. Discussion

The present data demonstrate that following glycogen depletion of either type I or type II muscle fibres, WEP and EP remain unchanged when compared to values attained with habitual glycogen levels. According to these data, glycogen either plays little part in determining the magnitude of W' or the level to which subjects were glycogen depleted was insufficient to significantly diminish sprint and/or endurance performance over a 3-min duration of all-out exercise. It would also appear that muscle glycogen content has little bearing on the magnitude of the EP or CP.

Based on previous research, it appears that glycogen is, whether relatively small or not, a contributing factor to the overall energy reserve available for severe-intensity work (Ferguson et al., 2010; Miura et al., 2000). The magnitude of glycogen depleted by the two depletion protocols in the present study

however, may have been insufficient to induce detectable reductions in W' using the 3-min all-out test. This may be because of the relatively short duration, yet maximal intensity, of the 3-min test. Previous literature has reported that for sprint cycle exercise of up to 90 s, muscle glycogen is reduced by only 33 % (Withers et al., 1991). This suggests that in the present study there was likely ample glycogen present in the muscle to complete 3-min of sprint cycling without a reduced glycogen content compromising the WEP or EP parameters. This may be especially true because from ~ 100 s onward, the power output of the 3-min test is typically similar to EP (Figure 5.3 p122); at such intensity, type I (and presumably type IIa) muscle fibres, resynthesising ATP via oxidative means, are likely to be the fibres left 'unfatigued' and thus the power output measured in the 3-min test will be largely aerobically generated. However, over the initial ~ 100 s, where both type I, IIa and IIx muscle fibres are likely maximally recruited, energy will be derived from predominantly anaerobic pathways (Gastin, 2001) before these higher order, rapidly-fatigueable fibres 'exhaust' leaving power output to be sustained via the lower order fibres. As both type I and type II muscle fibres were selectively depleted of their glycogen by the type I and type II depletion protocols respectively, it would appear, from the lack of difference in any 3-min test parameters under the extent of muscle glycogen depletion employed within this study, that glycogen contributes little toward WEP (W') or EP (CP) over 3-minutes of maximal exercise.

In the present study we attempted to deplete glycogen content in two specific muscle fibre populations based on the methods of Carter et al. (2004). Type I muscle fibres were targeted for depletion through a long duration (180 min) low intensity ($30\% \dot{V}O_{2max}$) cycle bout which has previously reduced muscle glycogen content of type I fibres by 44 % at the completion of the depletion bout. Type II muscle fibres were targeted through a series of (10) intermittent, high-intensity ($120\% \dot{V}O_{2max}$ power), short duration (1 min) cycling bouts, which were shown to deplete the muscle glycogen content of type II muscle fibres by 55 % (Carter, Pringle, Boobis, Jones, & Doust, 2004). In the Carter et al. (2004) study, subjects rested for 1 hour before completing a criterion bout of exercise. Ivy et al. (1988) present data showing a 4 mmol.kg^{-1} w.w. increase in muscle glycogen content within 2 hours post-completion of a 70 min exercise bout (6 x 8 min at $68\% \dot{V}O_{2max}$ followed by 2 min at $88\% \dot{V}O_{2max}$) when no carbohydrates

were consumed during or following exercise. The 1 hour between depletion bout and criterion bout in the Carter et al. (2004) study will have been insufficient for appreciable muscle glycogen synthesis and thus the criterion bout will have been performed under muscle glycogen conditions similar to those reported above (44 % Type I, 55 % Type II). However, Ivy et al. (1988) present data confirming that, even in the absence of carbohydrate consumption, following physically demanding exercise, muscle glycogen will synthesise to some extent. In the present study, subjects had an overnight rest (12 – 14 hours) and an evening meal (containing minimal carbohydrate) before their return to the laboratory the following morning for the 3-min test. This prolonged time-gap may have enabled muscle glycogen to synthesise (Ivy, Lee, Brozinick, & Reed, 1988; Raja et al., 2008), potentially to levels that could have attenuated the level of muscle glycogen depletion incurred during the preceding evening's depletion bouts. If this did occur, it would have lessened the extent of the glycogen depletion anticipated, based on the results of Carter et al. (2004). Conceivably, this (potentially) somewhat smaller magnitude of muscle glycogen depletion at 3-min test onset combined with the relatively small utilisation of muscle glycogen during sprint cycle exercise (Withers et al., 1991) could explain the similarity observed in 3-min test parameters between the three conditions (Table 5.1 p120).

Consideration should be given to the intensity of the type I glycogen depletion bout. In the present study 30 % $\dot{V}O_{2max}$ equated to 93 ± 11 % of the GET. Thus for most subjects the intensity of the depletion bout was in the moderate-intensity domain (power output below the power at GET). However, for some, this depletion bout was heavy-intensity exercise (above the GET, below the CP), corresponding to a more physiologically demanding exercise bout than intended. As exercise intensity increases, so too does the number of motor units recruited and the number of type II muscle fibres (Burnley et al., 2002; DiMenna, Wilkerson, Burnley, & Jones, 2008; Gaesser & Poole, 1996). The rate of muscle glycogen utilisation increases in proportion to the exercise intensity (van Loon et al., 2001). Thus, it appears likely that not all subjects entered the 3-min test following type I depletion in the same state of fibre-specific glycogen depletion; although without muscle biopsies to confirm this, the suggestion remains speculative. However, for those subjects who completed 3 hours in the

heavy-intensity domain, not only can we have expected greater muscle glycogen depletion, but more specifically, a greater depletion of type II muscle fibres (most likely type IIa). This could go some way to explaining the noticeable (yet not statistically different) reduction in WEP following the type I depletion trial and ostensibly the lack of difference in all-out test parameters between the two depletion protocols.

While we may have inadvertently depleted some type II fibres during our type I specific depletion protocol, we may have also not targeted type II fibres to the same extent as previous studies, during our type II depletion protocol. Carter et al. (2004; and similarly, Heigenhauser et al. 1983) had their subjects maintain a pedal rate of 60 rpm (50 rpm in the Heigenhauser et al., 1983 paper) during the 1 min exercise bouts at $120\% \dot{V}O_{2max}$. We allowed subjects to pedal at their preferred cadence to help enable them to overcome the very heavy resistance on the pedals during the repeated 1 min efforts. However, in doing so we may have negated the specific targeting of higher order type II muscle fibres (type IIb and IIx) for glycogen depletion (Ahlquist, Bassett, Sufit, Nagle, & Thomas, 1992). As muscles generate tension to produce force, a slower pedal rate requires a greater force per pedal stroke (Lucia, Hoyos, & Chicharro, 2001). As such, under greater tension (higher force) type II muscle fibres are called upon to help maintain or generate force (Jabre & Spellman, 1996). By increasing the pedal cadence during the type II depletion protocol we may have inadvertently reduced the number of type II fibres (certainly the higher order type IIx and type IIb) being recruited for the 1 min bouts when compared to completing the efforts at 60 rpm (Ahlquist et al., 1992). This may account, to some extent, for observing no differences in WEP or PPO following type II muscle fibre glycogen depletion, due to the highest order fibres' glycogen content potentially being uncompromised.

Whereas we observed no differences in WEP or EP following two differing glycogen depletion protocols, Miura et al. (2000) reported a reduction in W' as a result of a different glycogen depletion protocol. The notable difference between our depletion protocol and that of Miura et al. (2000) is that Miura and colleagues took their subjects to absolute exhaustion using both a heavy-intensity, 75 min cycle and subsequently, repeated 1 min efforts at 115

$\% \dot{V}O_{2max}$ (with 1 min rest interspersed) until the 1 min efforts could no longer be completed. This depletion protocol was expected to have depleted muscle glycogen content by 50 % without targeting a specific muscle fibre type. It is likely that this will have not only depleted a considerable percentage of the type I muscle fibres but also greatly depleted the type II fibres. Thus, the following day (having abstained from food) when subjects were asked to perform severe-intensity exercise to the limit of tolerance, it is conceivable that, the (presumably) low glycogen content in the higher-order fibres would have caused a relatively greater reduction in T_{lim} during the highest-intensity severe bouts which will require the greatest number of type II fibres to meet the external power demand. Perhaps unexpectedly, the tolerable duration of the least intense predicting trials were of a similar duration to those completed in the 'normal glycogen', control condition. Although no exhaustion times were explicitly published in the Miura et al. (2000) paper, figurative data clearly show the differences between conditions. The authors do not explain how they decided on the intensity of the constant-power trials and how they were amended for the glycogen depleted condition (which they clearly were based on their reported data). The reduction in the intensity of the two least severe predicating trials (compared to control) clearly enabled subjects to equal or surpass the exhaustion time of the control condition. However, exhaustive trials of longer durations lead to larger estimates of the W' parameter (Bishop et al., 1998) meaning in the Miura et al. (2000) paper, their methodological alterations should, if anything, bias the glycogen depleted W' parameter toward a higher value; potentially making it more difficult to observe the reduction in W' that they did. It should be noted, however, that the durations of the CP predicting trials in the Miura et al. (2000) paper were, at their shortest, less than 2 min and at their longest, shorter than 6 min in duration. These times are somewhat short of the 3 to 15 min duration recommended in the literature (Bishop et al., 1998; Hill, 1993; Poole et al., 1988; Poole et al., 1990). What must be considered is the impact of the glycogen depleting protocol itself on time to exhaustion the following morning. The tolerable duration of severe-intensity exercise may have been affected, or shortened as a result (at least in part) of residual muscle/neuromuscular fatigue following the prolonged, exhaustive glycogen-depleting bout the day prior to the CP predicting trial(s). In the normal glycogen condition, participants had been asked to rest and not engage in any strenuous

activity the day prior to a severe-intensity predicting trials. As such, the differences observed in exercise tolerance between normal and depleted glycogen conditions may have, to some extent, been accounted for by 'fatigue' in the glycogen-depleted state.

A facet not to be overlooked, given the maximal nature of the 3-min all out test, is the effect of the type I glycogen depletion bout on pedal cadence during the subsequent 3-min test. The type I depletion protocol required participants to maintain a cadence of 60 rpm, 20 – 35 rpm lower than that preferred by the subjects in the present study. As the depletion bout was of prolonged duration (180 min), this exercise bout could have affected the ability of some of the subjects to cycle at the leg speeds they were more familiar with; perhaps a down-regulation of pedal speed due to the prolonged bout at a cadence of 60 rpm (Kanehisa & Miyashita, 1983). The present results (Table 5.1 p120) indicate a marked reduction in peak cadence and a relatively marked reduction in PPO following the type I depletion protocol when compared to the other conditions (although no statistical difference was observed $P = 0.423$). We would have expected to have observed these types of trends following the depletion of type II fibres due to the inherent ability of type II muscle fibres to produce high force at speed (peak powers). Although no statistical difference was observed, a ~ 50 W reduction in PPO, and thus a ~ 1.5 kJ reduction in WEP, would cause substantial differences in sprint cycle performance compared to having completed a shorter, more intense, but higher cadence, work bout (or nothing at all) on the day prior.

A novel finding of this research that should not be overlooked is that the 3-min all-out test can be performed equally well when prolonged low-intensity exercise or severe-to-extreme-intensity interval training has been performed the day prior to the test. Previously the 3-min all-out test has been conducted when subjects have observed 24 hours of rest prior to completing the test (Burnley et al., 2006a; Vanhatalo et al., 2007, 2008a, 2008b; Vanhatalo & Jones, 2009b). The present data clearly shows that for all-out exercise lasting 3 min, performing exercise, not typically part of the participants' habitual activity and which was specifically designed to cause glycogen depletion in the muscles used whilst cycling, has no effect on the power profile and parameters of the 3-min all-out

cycling test. As well as obtaining values for EP and WEP from the 3-min all-out test, $\dot{V}O_2$ projects toward and remains within 5 % of $\dot{V}O_{2max}$ (typically) during the test (Burnley et al., 2006a; Vanhatalo et al., 2007, 2008a, 2008b; Vanhatalo & Jones, 2009b). As such, the test may provide a very useful tool with which to monitor physiological adaptations to training without causing considerable disruption to training programmes.

In summary, the present data suggest that reduced muscle glycogen content has no effect on the ability to perform maximal exercise of 3-min duration. This was evident from the similarity in the EP and WEP parameters of the 3-min all-out test following both type I and type II specific muscle fibre glycogen depletion when compared to a control condition. Whereas for the conventional assessment of CP and W' , glycogen content of the muscle appears to influence the W' , supporting the suggestion that muscle glycogen comprises part of the physiological constituents of this parameter, the present data suggest that the level of glycogen depletion imposed here, was insufficient to limit prolonged sprint performance.

Perspective 2

Whereas in chapter 4 the 3-min all-out test appeared to be able to detect expected reductions in the W' , the 3-min test may not be sensitive enough to detect any reduction in W' as a result of reduced muscle glycogen content. Conversely, the extent of muscle glycogen depletion likely induced with the protocol employed within chapter 5 may have been insufficient for glycogen to become limiting to power output over a 3-min duration of maximal effort. However, the possibility that muscle glycogen content does not in fact comprise part of the W' can still not be ruled out. What cannot be denied is that some level of muscle glycogen depletion or even prior prolonged or interval exercise had no effect on the parameters obtained from the 3-min all-out test. Any intervention that alters the CP provides an opportunity to investigate the response of the W' (and vice versa). One such intervention known to have a marked effect on the CP is hypoxia. Through inducing a reduction in the CP and $\dot{V}O_{2\max}$, and effectively 'shifting' the power outputs between which the severe-intensity domain resides, provides an opportunity to study the response of the W' . The W' has been proposed to represent the relative 'size' of the severe-intensity domain and thus if CP and $\dot{V}O_{2\max}$ are similarly affected by hypoxia, the W' , and importantly the WEP of the all-out test, should remain unaffected.

Chapter 6 – Influence of hypoxia on the power-duration relationship during high-intensity exercise

6.1. Introduction

Recent studies indicate that the CP and W' parameters might not be entirely independent. For example, it has been shown that W' tends to decrease subsequent to a training intervention which significantly increases the CP (Jenkins & Quigley, 1992; Vanhatalo et al., 2008a). Similarly, Vanhatalo et al. (2010) reported a significant increase in CP and a significant reduction in W' in hyperoxia compared to normoxia, with the changes in CP and W' being inversely correlated. These findings suggest that, rather than representing an 'anaerobic capacity', the W' may be related to the magnitude of the 'gap' separating the CP and the $\dot{V}O_{2\text{peak}}$ (Burnley & Jones, 2007). To our knowledge, the relationship between changes in $CP/\dot{V}O_{2\text{peak}}$ and changes in W' consequent to an intervention has not been investigated.

It is well documented that reductions in the inspired fraction of O_2 result in impaired performance during high-intensity exercise lasting longer than approximately 60 s (e.g., (Calbet, De Paz, Garatachea, Cabeza de Vaca, & Chavarren, 2003; Weyand et al., 1999)). Recently, Dekerle et al. (2012) reported a 14 % reduction in CP and an unchanged W' in acute moderate hypoxia ($F_iO_2 = 0.15$) compared to normoxia. The relative impact of hypoxia on the $\dot{V}O_{2\text{peak}}$ and CP (i.e., the 'range' of the severe-intensity exercise domain) and the W' was not examined. Furthermore, the 3-min all-out cycling test has yet to be employed in hypoxia. Hypoxia represents a potentially powerful intervention to alter the parameters of the P-D relationship, as assessed using conventional testing procedures, and therefore provides an opportunity to test whether any such changes are faithfully tracked by the parameter estimates derived from the 3-min all-out test.

In the present study, we investigated the influence of moderate normobaric hypoxia ($F_{iO_2} = 0.13$) on the parameters of the P-D relationship measured both by conventional procedures (5 prediction trials; (Bishop et al., 1998)) and the 3-min all-out test. We hypothesized that: 1) relative to normoxia, hypoxia would reduce the CP but not alter the W' ; 2) the 3-min all-out test would provide estimates of CP and W' that were not different from those derived from conventional testing procedures either in normoxia or hypoxia; and 3) there would be a positive relationship between $\Delta CP/\dot{V}O_{2max}$ and $\Delta W'$ in hypoxia compared to normoxia.

6.2. Methods

6.2.1. Subjects

Thirteen recreationally active females (mean \pm SD: age 21 ± 1 yr, body mass 69.2 ± 11.9 kg, height 1.66 ± 0.05 m) volunteered and provided written informed consent to participate in this study, which had received approval from the local research ethics committee. None of the participants reported a history of chronic exposition to altitude. Female participants were recruited due to their typically smaller V_E during severe-intensity exercise and our equipment constraints; that being a 1000 L reservoir of hypoxic air and exhaustive exercise trials designed to endure up to 15 min. Participants were required to visit the laboratory on 14 occasions over a 4-5 week period. A minimum of 24 hours separated each visit. Participants were fully familiarized with all testing procedures prior to any experimentation. For each visit, participants were asked to arrive at the laboratory rested (no strenuous exercise performed in the preceding 24 h), fully hydrated, at least 3 h postprandial, and having avoided alcohol and caffeine for the preceding 12 and 6 h, respectively.

6.2.2. Experimental design

All of the experimental procedures were carried out in a laboratory at sea level. All tests were carried out in both normoxia and hypoxia. Initially, participants completed a ramp incremental test for the determination of $\dot{V}O_{2peak}$ and GET. The participants also completed five constant-load tests to the limit of tolerance,

and a 3-min all-out test. Visits were randomized subsequent to the completion of the two ramp-incremental tests (in normoxia and hypoxia). In all testing except the all-out cycling tests, participants were asked to maintain their self-selected cadence (± 5 rpm). Throughout all testing, participants were asked to remain seated on the ergometer, and strong verbal encouragement was provided by the experimenter. Participants were blinded to the F_{iO_2} for each exercise test. All testing was preceded by 5 min of 'unloaded' cycling (20 W) whilst inhaling the given gas mixture for the test in order to equilibrate the body O_2 stores (Linnarsson, Karlsson, Fagraeus, & Saltin, 1974).

6.2.3. Equipment

All exercise tests were performed on an electromagnetically-braked cycle ergometer (Excalibur Sport, Lode, Groningen, Netherlands) with continuous breath-by-breath pulmonary gas exchange measurement (Oxycon Pro, Jaeger, Hoechberg, Germany). The mouthpiece assembly of the analyzer was modified using a Hans Rudolph valve system, allowing the inspirate to be derived from a Douglas bag (hypoxia) or ambient air (normoxia). Air entered the mouthpiece assembly through a one-way valve before being inspired by the subject through the gas analyzer's 'triple V' mouthpiece assembly. Expired air was passed back through the 'triple V' entering the Hans-Rudolph assembly, and exiting through a second one-way valve. Ambient air was filtered using a commercially available device (CAT-11, Colorado Altitude Training, Colorado, USA), generating a low F_{iO_2} gas mixture. This low F_{iO_2} gas mixture was pumped into a Douglas bag (volume = 1000 L). The O_2 concentration of the Douglas bag was continually monitored using a digital combined O_2 and CO_2 analyzer (Servomex 5200S, Zoetermeer, Netherlands) and was held at 0.128 ± 0.02 . The Douglas bag was inflated and the same mouthpiece assembly was used for all visits in order to ensure that the participant was blind to the F_{iO_2} of the inspired air.

Fingertip blood samples were taken for assessment of whole blood lactate concentration (YSI Stat 2300, Yellow Springs, OH) prior to the start of each exercise test and at the limit of tolerance (prediction trials) or at the end of the test (all-out tests). Arterial O_2 saturation was determined non-invasively

throughout all testing by pulse oximetry (7500FO, NONIN, Minnesota, USA; S_pO_2), via an infrared probe placed on the fingertip.

6.2.4. Incremental test

The ramp-incremental protocol consisted of 5 min of unloaded pedaling, followed by a ramp increment in power output of $25 \text{ W}\cdot\text{min}^{-1}$ until volitional exhaustion. See section 3.4 for incremental test methods.

6.2.5. Power-duration relationship

The CP and W' were estimated from five prediction trials in both normoxia and hypoxia. The power outputs for these trials were chosen to obtain a time to exhaustion ranging between 2 and 15 minutes (Bishop et al., 1998; Hill, 1993; Poole et al., 1988). Each trial was preceded by 5 min of unloaded pedaling, and participants were instructed to maintain their preferred cadence for as long as possible. A test was terminated when cadence fell by more than 10 rpm below the preferred cadence for > 5 s. Strong verbal encouragement was given throughout, and time to exhaustion was recorded to the nearest second. Participants remained blind to the power outputs and their performance times in the prediction trials until all testing had been completed. Linear regression was used to provide two sets of CP and W' estimates from the results of the prediction trials, using the work-time ($W = CPt + W'$) and the 1/time ($P = W'(1/t) + CP$) models. The model providing the lowest standard errors and the highest R^2 was chosen to provide the CP and W' parameter estimates.

6.2.6. All-out cycling test

Following familiarization (all participants completed at least one full all-out cycling test prior to any experimentation) participants completed three all-out cycling tests in a random order; (i) in normoxia with normoxia-specific resistance (N); (ii) in hypoxia with normoxia-specific resistance (HN); and (iii) in hypoxia with hypoxia-specific resistance (HS). It has been demonstrated that a significantly larger estimate for W' is attained when a greater fixed resistance is used during the all-out cycling test (Vanhatalo et al., 2008b), which would effectively be the scenario if the ergometer resistance was not adjusted to

account for the lower P_{ramp} and GET noted in the ramp test conducted in hypoxia. See Section 3.6 for all-out test methods and instructions.

6.2.7. Statistical analysis

Responses within environmental conditions were analyzed using a one-way repeated measures ANOVA with a Bonferroni adjustment made to the alpha level for post-hoc analysis of differences. Differences between F_{iO_2} conditions, and comparisons between estimates of CP and W' via conventional and all-out methods, were assessed using paired-samples t -tests. Correlation coefficients and bias \pm 95 % limits of agreement were used to assess the relationships between the CP and W' as estimated via conventional and all-out methods. Relationships were assessed using Pearson product moment correlation coefficients. Statistical significance was accepted at $P < 0.05$. Results are reported as mean \pm SD.

6.3. Results

The $\dot{V}O_{2\text{peak}}$ (and P_{ramp}) values measured during the ramp incremental test in normoxia and hypoxia were $2.88 \pm 0.44 \text{ L}\cdot\text{min}^{-1}$ ($246 \pm 30 \text{ W}$) and $2.34 \pm 0.27 \text{ L}\cdot\text{min}^{-1}$ ($211 \pm 20 \text{ W}$), respectively, with the $\dot{V}O_{2\text{peak}}$ (and P_{ramp}) both being significantly higher in normoxia ($P < 0.01$). The GET (and corresponding power) were also higher ($P < 0.01$) in normoxia ($1.48 \pm 0.20 \text{ L}\cdot\text{min}^{-1}$ and $93 \pm 18 \text{ W}$) than in hypoxia ($1.28 \pm 0.18 \text{ L}\cdot\text{min}^{-1}$ and $75 \pm 15 \text{ W}$). The power output corresponding to 50 % Δ was $170 \pm 22 \text{ W}$ in normoxia and $143 \pm 14 \text{ W}$ in hypoxia ($P < 0.001$).

Table 6.1. Mean (\pm SD) data from conventional exhaustive exercise trails.

	Power Output (W)		$\dot{V}O_2$ peak ($L \cdot min^{-1}$)		Time to exhaustion (s)	
	Normoxia	Hypoxia	Normoxia	Hypoxia	Normoxia	Hypoxia
Trial 1	191 \pm 24	150 \pm 18*	2.81 \pm 0.36	2.34 \pm 0.28*	792 \pm 137	748 \pm 179
Trial 2	201 \pm 25	160 \pm 18*	2.90 \pm 0.33	2.36 \pm 0.21*	474 \pm 98	485 \pm 103
Trial 3	216 \pm 26	177 \pm 16*	2.96 \pm 0.41	2.35 \pm 0.26*	322 \pm 60	304 \pm 48
Trial 4	229 \pm 27	189 \pm 18*	2.92 \pm 0.44	2.28 \pm 0.26*	237 \pm 25	236 \pm 34
Trial 5	242 \pm 29	203 \pm 19*	2.85 \pm 0.39	2.28 \pm 0.24*	182 \pm 18	188 \pm 16

* denotes significantly different to corresponding normoxia trial ($P < 0.001$).

6.3.1. CP and W' estimates from the conventional protocol

The durations of each corresponding prediction trial in normoxia and hypoxia were not different, with the shortest being 182 \pm 18 and 188 \pm 16 s and the longest being 792 \pm 137 and 748 \pm 179 s for normoxia and hypoxia. Arterial O₂ saturation at test cessation was significantly reduced in hypoxia compared to normoxia (76 \pm 5 % vs. 92 \pm 7; $P < 0.001$). The $\dot{V}O_{2peak}$ attained during each of the five prediction trials in each condition was not different to the $\dot{V}O_{2peak}$ measured in the corresponding ramp incremental test (Table 6.1 p136). However, the $\dot{V}O_{2peak}$ values attained across all hypoxic trials were significantly lower than the normoxic $\dot{V}O_{2peak}$ values ($P < 0.001$; Table 6.1 p136).

Table 6.2. Mean (\pm SD) 3-min all-out test variables from each condition.

	Normoxia	Hypoxia-Specific	Hypoxia (normoxic resistance)
EP (W)	172 \pm 30 ^{b,c}	134 \pm 23 ^a	135 \pm 26 ^a
WEP (kJ)	12.0 \pm 2.6 ^c	12.5 \pm 1.4 ^c	13.9 \pm 2.8 ^{a,b}
PPO (W)	512 \pm 78 ^b	453 \pm 57 ^{a,c}	515 \pm 81 ^b
Work done (kJ)	43.0 \pm 5.8 ^{b,c}	36.6 \pm 4.5 ^{a,c}	38.1 \pm 5.1 ^{a,b}
Peak cadence (rpm)	128 \pm 9	131 \pm 8	128 \pm 9
$\dot{V}O_{2peak}$ (L \cdot min ⁻¹)	2.82 \pm 0.37 ^{b,c}	2.30 \pm 0.30 ^a	2.28 \pm 0.23 ^a
SpO ₂ (%)	90 \pm 6	79 \pm 5 ^a	78 \pm 5 ^a
$\dot{V}O_{2peak}$ (% of corresponding ramp test $\dot{V}O_{2max}$)	98 \pm 3	98 \pm 2	97 \pm 3

^a denotes a significant difference to normoxia ($P < 0.01$)

^b denotes a significant difference to hypoxia-specific conditions ($P < 0.05$)

^c denotes a significant difference to hypoxia (normoxia-resistance) ($P < 0.01$).

There were no differences in parameter estimates derived from the work-time and 1/time models. The R^2 for the work-time model was 0.998 ± 0.003 (range 0.993-0.999) and the R^2 for the 1/time model was 0.952 ± 0.04 (range 0.900 and 0.999). As the estimates derived from the work-time model were associated with a lower SEE, the results from this model were used for further analysis. The SEE for the CP was 3 ± 2 W and 4 ± 2 W for normoxia and hypoxia, respectively. The 95 % confidence intervals for CP in normoxia and hypoxia were ± 18 W and ± 26 W respectively. The SEE for the W' was 1.3 ± 0.7 kJ and 1.8 ± 0.8 kJ for normoxia and hypoxia, respectively. The 95 % confidence intervals for normoxia and hypoxia were ± 8.21 and ± 9.56 kJ respectively. The CP was significantly reduced (range -19 to -34 %) in hypoxia compared to normoxia (132 ± 17 W vs. 175 ± 25 ; $P < 0.001$) The W' was not significantly different in hypoxia compared to normoxia (12.3 ± 2.7 vs. 13.2 ± 2.2 kJ; $P > 0.05$), but there was appreciable inter-individual variability (range -44 to +38 %). The $\% \Delta CP$ was significantly correlated with the $\% \Delta W'$ ($r = -0.72$, $P < 0.05$; Figure 6.1 p138). Moreover, there was a significant relationship between the $\% \Delta CP / \dot{V}O_{2peak}$ and the $\% \Delta W'$ ($r = 0.83$, $P < 0.001$; Figure 6.2 p139).

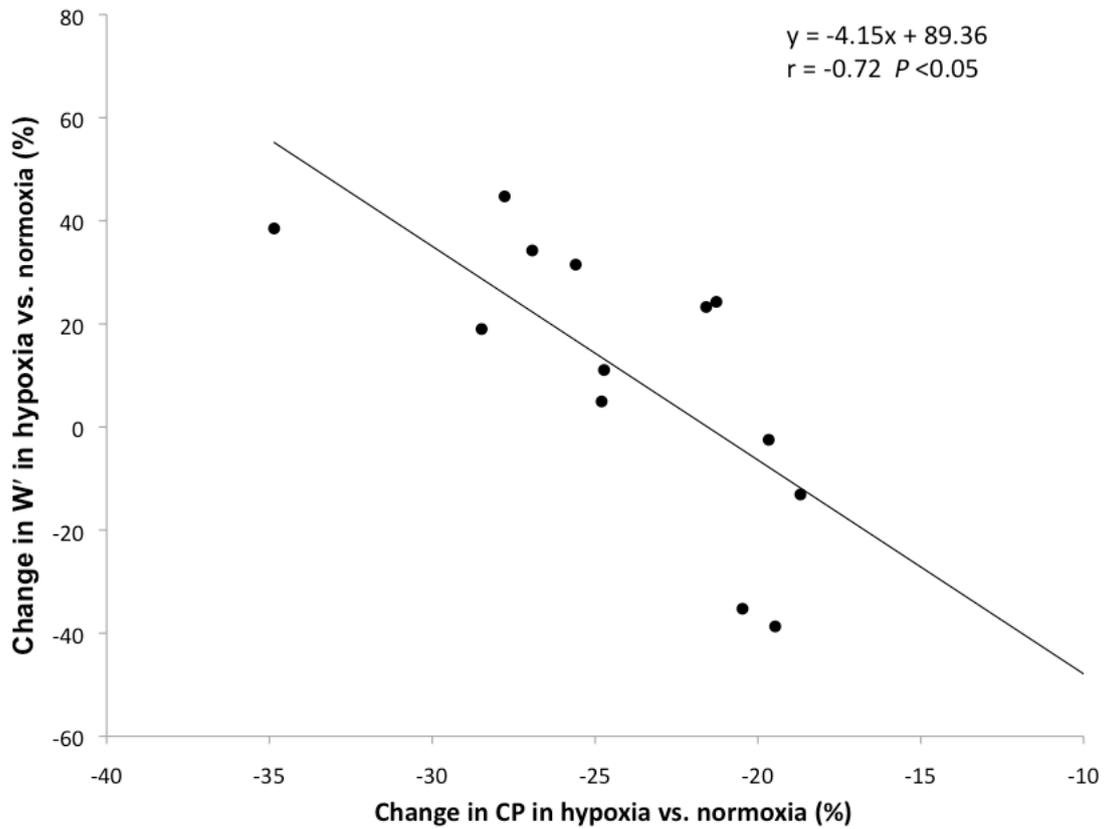


Figure 6.1. Relationship between change in W' and change in CP.
 There was a significant negative relationship between the % change in W' and the % change in CP in hypoxia vs. normoxia.

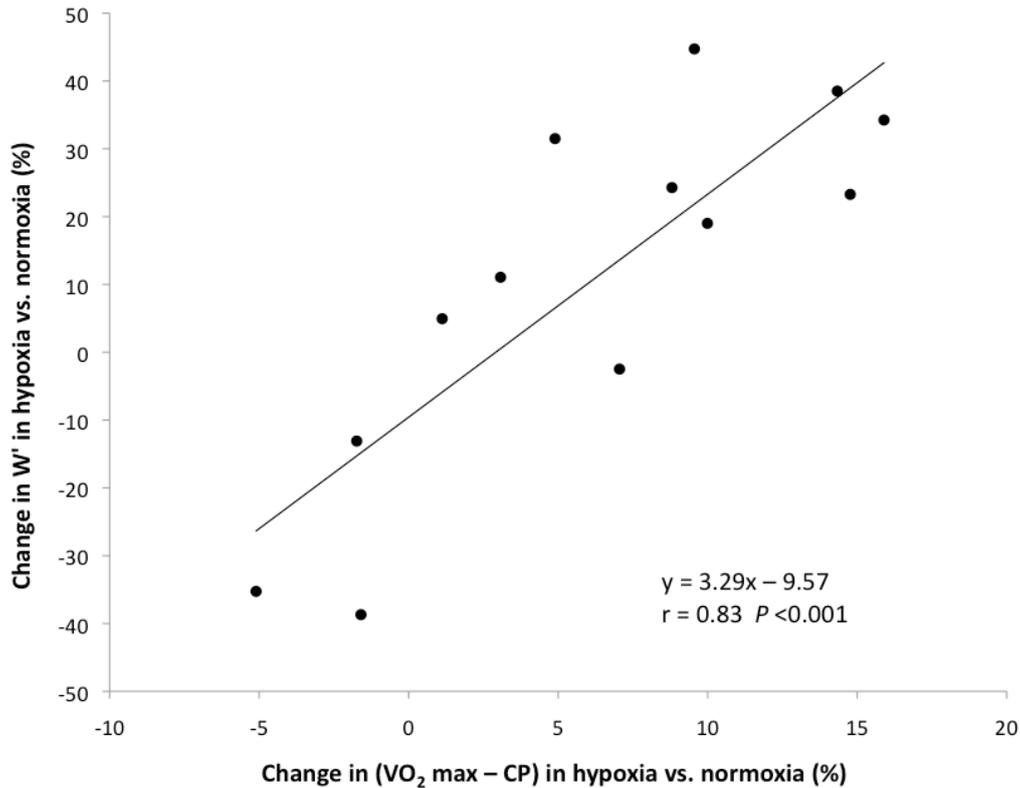


Figure 6.2. Relationship between change in W' and the change in $\dot{V}O_{2peak} - CP$.

There was a significant relationship between the % change in $(\dot{V}O_{2peak} - CP)$ and the % change in W' in normoxia vs. hypoxia.

6.3.2. CP and W' estimates derived from the all-out test

The EP and WEP parameters determined via the 3-min all-out cycling test are shown in Table 6.2 p137 and the mean power profiles for each of the 3-min tests are displayed in Figure 6.3 p140. The EP was significantly lower in hypoxia (range -10 to -32 %) compared to normoxia ($P < 0.001$), irrespective of the ergometer-resistance used; however, the EP was not different between the two all-out tests in hypoxia (i.e. HN vs. HS). The WEP was not different between normoxia and hypoxia when the ergometer resistance was adjusted appropriately (i.e. N vs. HS), but WEP was significantly higher than both N and HS when the test was conducted in hypoxia with the normoxia resistance applied (HN). Total work done was significantly different between all conditions, with the most work done in N, and the least in HS ($P < 0.01$). Peak power output was significantly lower in HS compared to the other two conditions, but

there were no significant differences in peak cadence across the three tests. The $\dot{V}O_{2peak}$ during the all-out tests was significantly reduced in hypoxia compared with normoxia ($P < 0.001$) but was not different between the two hypoxic tests. The $\dot{V}O_{2peak}$ in each of the 3-min tests was not significantly different from the respective ramp incremental test $\dot{V}O_{2peak}$ ($P > 0.05$ for all).

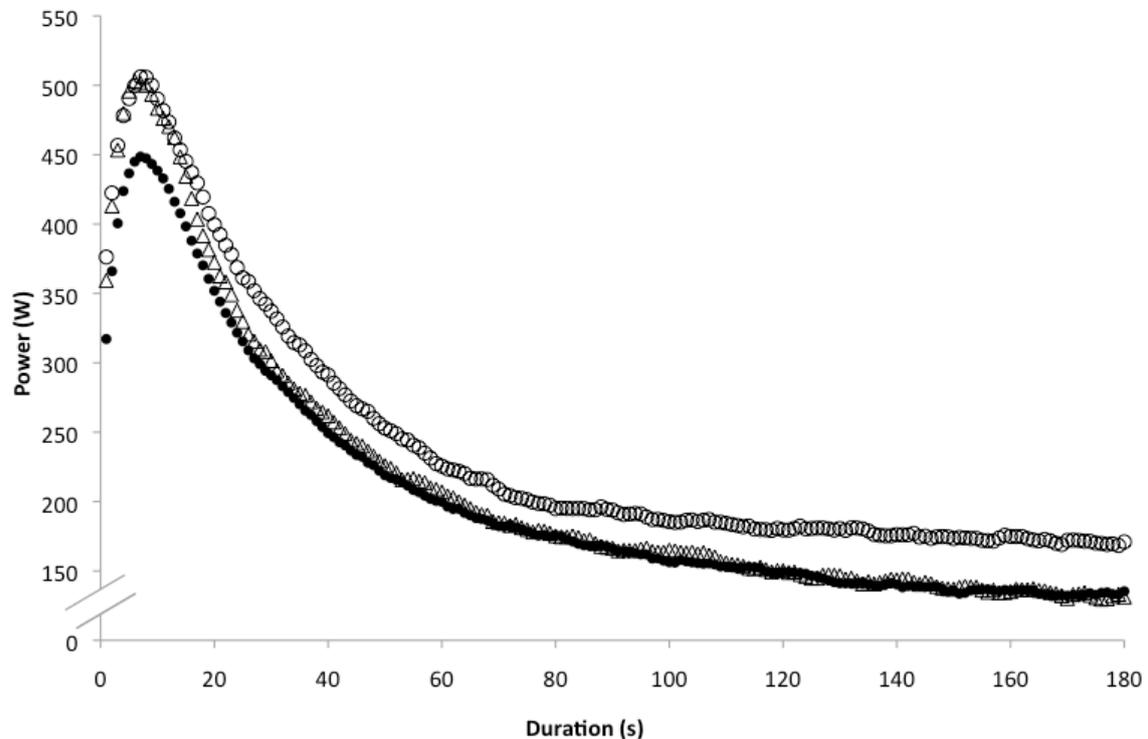


Figure 6.3. Mean 3-min power profiles from each test condition.

Mean power profiles for the 3-min all-out cycling tests. Open circles (○) represent the normoxic condition; closed circles (●) show the hypoxia specific condition; and open triangles (Δ) represent the hypoxic condition (with normoxia resistance applied). Note the leveling out of the power output during the last 45 s of each test (CP). The WEP is calculated as the work done above the EP.

6.3.3. Comparisons between conventional and all-out test CP and W' estimates

There were no significant differences in CP estimates derived from the conventional method and the all-out test in either normoxia or hypoxia. Figure 6.4 p141 illustrates the relationships and bias \pm 95 % limits of agreement between the estimates of CP derived via conventional and all-out methods. The correlation coefficient for the two methods was $r = 0.88$ for normoxia and $r = 0.81$ for hypoxia, and the TE was 12 ± 8 W for normoxia and 10 ± 8 W for hypoxia. There were no differences in the estimates of W' between the two methods in normoxia or hypoxia. The correlation coefficients for the two

methods were $r = 0.48$ and $r = 0.22$, and the TE was 2.5 ± 1.3 kJ and 2.3 ± 1.5 kJ for normoxia and hypoxia, respectively (Figure 6.5 p142).

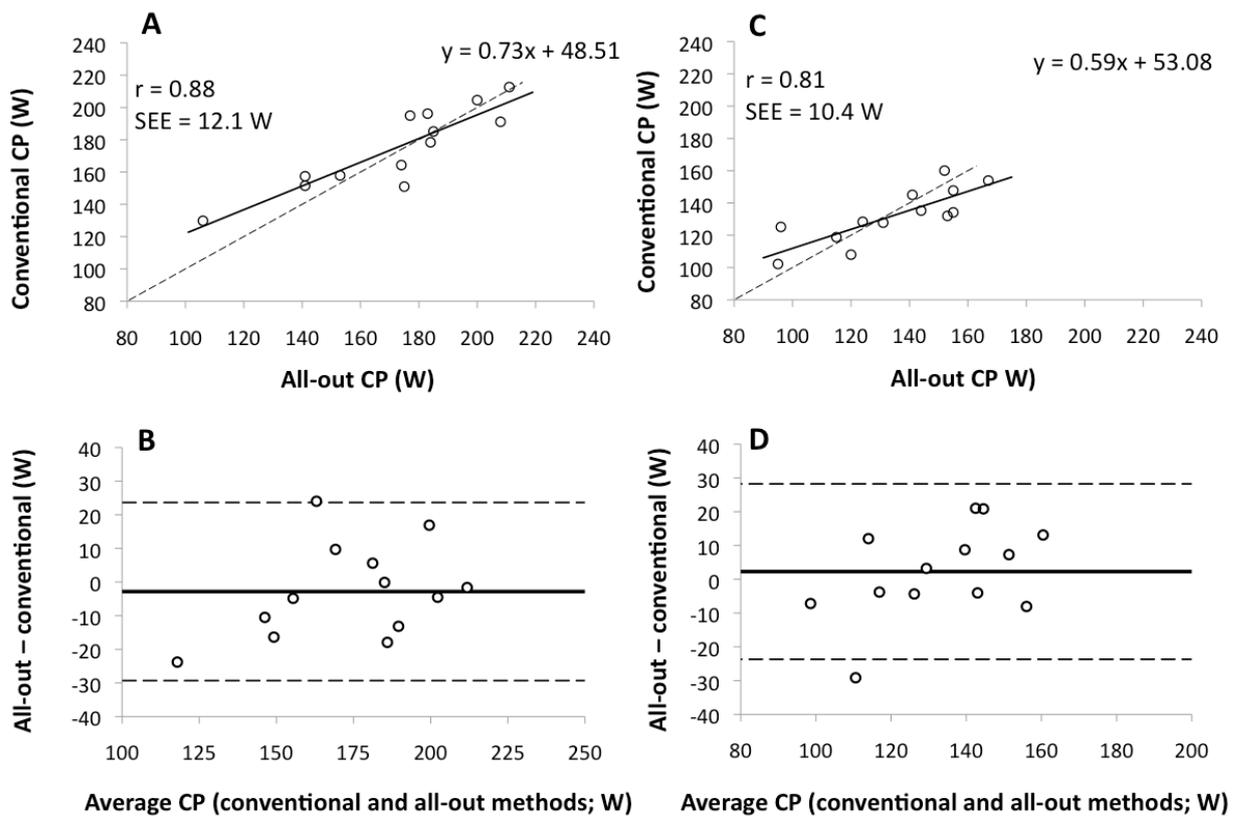


Figure 6.4. Validity and agreement between all-out and conventional CP. Limit of agreement plots of the relationships (A and C) and limits of agreement (B and D) between CP as determined by conventional and all-out methods. A and B are data from the normoxia condition, C and D are data from the hypoxia condition. The solid horizontal line in panels B and D represents the mean difference between estimates of CP between the two methods, and the dashed lines represent the 95 % limits of agreement.

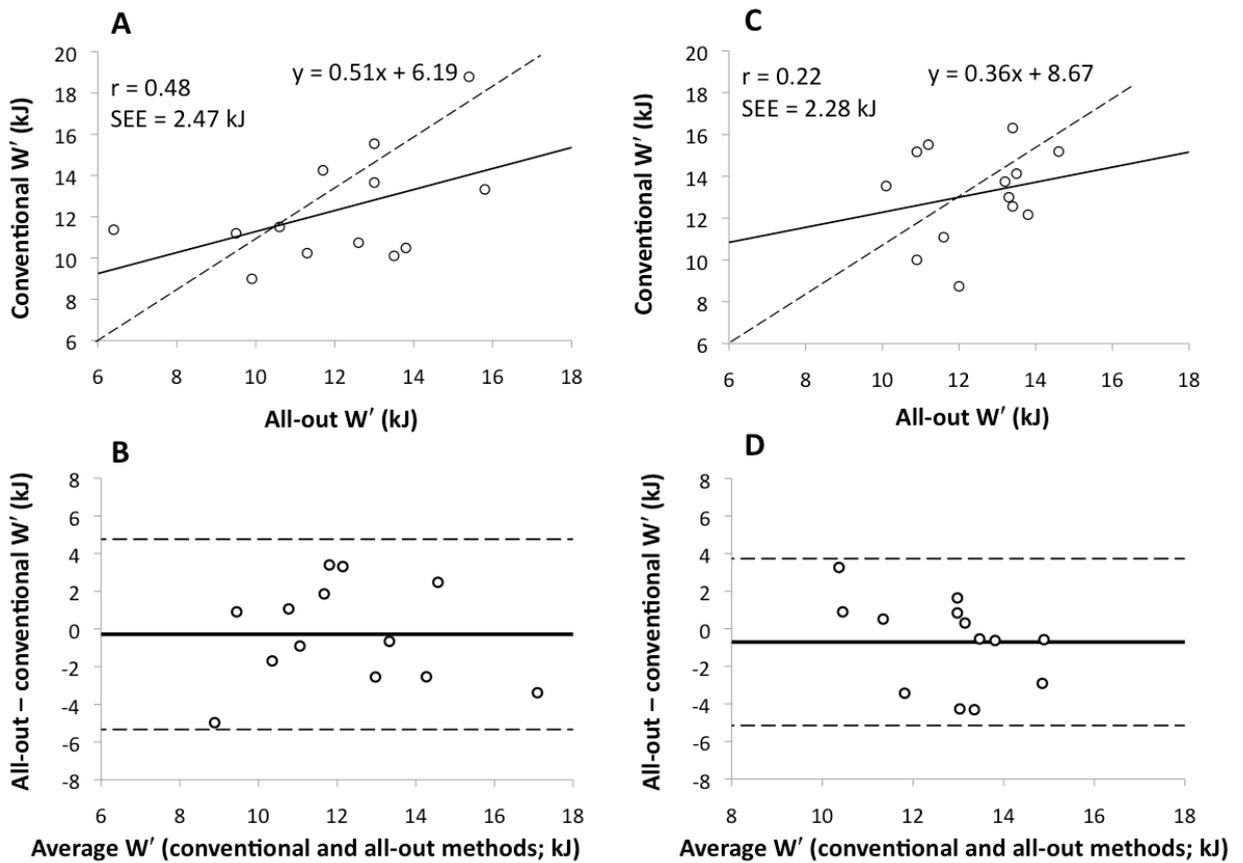


Figure 6.5. Validity and agreement between all-out and conventional W' .

Limit of agreement plots of the relationships (A and C) and limits of agreement (B and D) between W' as determined by conventional and all-out methods. A and B are data from the normoxia condition, C and D are data from the hypoxia condition. The solid horizontal line in panels B and D represents the mean difference between estimates of W' between the two methods, and the dashed lines represent the 95 % limits of agreement.

Discussion

This is the first study to examine the impact of moderate hypoxia ($F_iO_2 = 0.13$) on the CP and W' as measured using both conventional methods and the 3-min all-out test. In accordance with our hypotheses, we found that: 1) relative to normoxia, hypoxia significantly reduced the CP but did not significantly alter the W' ; 2) the 3-min all-out test provided estimates of CP and W' that were not different from those derived from conventional methods either in normoxia or hypoxia; and 3) there was a significant correlation between the $\Delta CP/\dot{V}O_{2peak}$ and the $\Delta W'$ in hypoxia compared to normoxia. These results confirm that the CP is a parameter of oxidative function, and indicate that the 3-min all-out test is a

valid method for determining the P-D relationship, both in normoxia and hypoxia. The results also suggest that the W' may not simply represent a store of 'anaerobic' energy, and support the notion that changes in W' consequent to an intervention may be related to changes in $CP/\dot{V}O_{2peak}$ (Burnley & Jones, 2007).

It is well documented that hypoxia results in reductions in $\dot{V}O_{2peak}$ (Amann et al., 2007; Weyand et al., 1999) and impairments in exercise performance (Calbet et al., 2003; Hogan, Richardson, & Haseler, 1999) compared to exercise in normoxia. In the present study, we investigated the effect of hypoxia on the P-D relationship using robust conventional methods (with five prediction trials) and a single 3-min all-out test. Our results indicate that the CP is systematically reduced in moderate hypoxia, whereas the impact on W' is variable and related to the relative impact of hypoxia on the $\dot{V}O_{2peak}$ and the CP. The relationship between $\Delta CP/\dot{V}O_{2peak}$ and $\Delta W'$ indicates that if hypoxia reduces the $\dot{V}O_{2peak}$ more than it reduces the CP, the relative range of the severe-intensity domain will become smaller and the W' will be reduced, and *vice versa*. Constant-power output exercise within the severe-intensity domain results in the development of a $\dot{V}O_2$ 'slow component' that will drive $\dot{V}O_2$ to its maximum value if the subject continues the exercise to exhaustion (Hill et al., 2002; Poole et al., 1988). The development of the $\dot{V}O_2$ slow component during severe-intensity exercise occurs concomitantly with the utilisation of the W' , with exhaustion coinciding with the attainment of $\dot{V}O_{2peak}$ and the complete depletion of the W' . It has been shown that the relative size of the $\dot{V}O_2$ slow component is related to the size of the W' (Murgatroyd et al., 2011; Vanhatalo et al., 2010a). Changes to the power output range between the CP and $\dot{V}O_{2peak}$ resulting from an intervention (such as training, hypoxia or hyperoxia) would therefore simultaneously alter the amplitude of the $\dot{V}O_2$ slow component and the size of the W' (Burnley & Jones, 2007).

The results of the present study are consistent with Dekerle et al. (2012) who also found that moderate hypoxia elicited a significant reduction in CP without significantly altering W' . In both studies there was significant inter-individual variability in the changes to W' in hypoxia and a significant negative relationship between the % change in CP and the % change in W' (i.e., individuals with

greater reductions in CP had smaller changes in W' in hypoxia) compared to normoxia. Interestingly, Vanhatalo et al. (2010) noted a significant inverse correlation between the increase in CP and the decrease in W' induced by hyperoxia ($F_{iO_2} = 0.70$). In the present study, a significant relationship was also observed between the $\Delta CP/\dot{V}O_{2peak}$ and the $\Delta W'$. Collectively, these results are contrary to the notion that the W' represents a fixed amount of 'anaerobic' energy (Monod & Scherrer, 1965), because changing muscle O_2 availability by breathing hypoxic or hyperoxic gas mixtures would be expected to alter oxidative but not non-oxidative metabolism across a whole bout of exercise conducted to exhaustion. Instead, the results add support to the suggestion that the magnitude of W' might be limited by the accumulation of fatigue-related metabolites and/or the depletion of muscle energy substrates (especially PCr), such that exercise above CP terminates upon the attainment of a 'critical tolerable limit' (Burnley & Jones, 2007; Jones et al., 2008; Poole et al., 1988; Vanhatalo et al., 2010a). The high [ADP], [P_i], and [Cr] at this 'critical tolerable limit' (when W' approaches zero) would provide a potent stimulus to mitochondrial respiration and promote the attainment of $\dot{V}O_{2peak}$ (Vanhatalo et al., 2010a).

Valli et al. (2011) also reported a 34 % reduction in CP in hypoxia but, in contrast to the findings of the present study and those of Dekerle et al. (2012), found a significant 45 % reduction in W' in hypoxia. A key difference between these studies is that, rather than have participants inspire a hypoxic gas mixture in normobaria ((Dekerle et al., 2012); present study), Valli et al. (2011) compared the P-D relationship at sea-level to that determined at high altitude (5050 m, equivalent to an F_{iO_2} of ~ 0.11). The authors suggested that the reduction in W' may be, in part, related to a reduction in muscle-venous O_2 storage at altitude. However, a reduction in O_2 stores at altitude would seem unlikely to account for the extent of the reduction in W' (4.9 kJ) reported by Valli et al. (2011). One possible explanation for these discrepant results regarding W' is the change in the relative importance of central compared to peripheral fatigue as F_{iO_2} is lowered. During moderate hypoxia ($F_{iO_2} \sim 0.13-0.15$), peripheral muscle fatigue appears to limit exercise tolerance to a similar extent as in normoxia (Amann et al., 2007). However, as the severity of hypoxia increases, eliciting S_pO_2 of ≤ 75 %, exercise is terminated before peripheral

factors likely become limiting (Amann et al., 2007). The mean S_pO_2 during the exhaustive prediction trials conducted at high altitude in Valli et al. (2011) was $73 \pm 7 \%$. This is substantially lower than in the present study, and below the threshold proposed by Amann et al. (2007) wherein central fatigue may become dominant. It is possible that the hypoxemia experienced at high altitude by the participants in Valli et al. (2011) resulted in early termination of exercise due to central fatigue and that the shorter exercise times impacted negatively on both CP and W' .

The results of the present study show that the 3-min all-out test provides an estimate of CP that is not significantly different from, and is highly correlated ($> r = 0.80$) and has good agreement with, the CP as estimated using conventional methods in both normoxia and hypoxia. This supports, and extends to hypoxia, earlier studies which indicated that the all-out test is a viable alternative method for assessing CP (Burnley et al., 2006a; Vanhatalo et al., 2007, 2008a, 2008b). The all-out test also provided estimates of W' that were not significantly different from those produced using conventional procedures in normoxia and hypoxia (when the fixed resistance was set according to performance in the ramp incremental test conducted in hypoxia; see below). It should be noted, however, that no significant correlation was observed between the W' estimates derived via the two different methods. It is possible that this lack of correlation is related to the different ways in which the W' is estimated with the conventional and all-out methods. Using conventional methodology, the W' is a function of the $\dot{V}O_{2peak}$ (or, more precisely, the severe-extreme exercise intensity domain boundary) and the CP, whereas in the all-out test, the calculation of the WEP is a function of the EP and the PPO. Despite this lack of correlation, from a practical perspective the EP and WEP estimates derived from the all-out test have been shown to provide accurate prediction of time to exhaustion over a wide range of exercise test modalities and pacing strategies within the severe-intensity domain (Bailey, Vanhatalo, DiMenna, Wilkerson, & Jones, 2011; Chidnok et al., 2013a; Vanhatalo et al., 2007).

Power output during the all-out test is directly related to cadence and ergometer resistance. As the peak cadence during the test is typically unaffected by small manipulations in ergometer resistance (Table 6.2 p137), a larger resistance will

result in a greater peak power output at the start of the test for a given cadence (Vanhatalo et al., 2008b). When a large peak power is attained at the beginning of the test relative to the power attained at the end of the test, a large W' is observed. This explains the significantly larger W' in the HN test compared to the N and HS tests and emphasizes the importance of adjusting the ergometer resistance according to appropriate ramp test data (e.g., pre- and post-training intervention; (Vanhatalo et al., 2008a)). In contrast, the EP from the all-out test, although reduced in hypoxia, was not affected by the ergometer resistance. The robustness of EP to the manipulation of ergometer resistance has been reported previously (Vanhatalo et al., 2008b).

In conclusion, moderate hypoxia alters the P-D relationship in recreationally active females. Specifically, compared to normoxia, the CP was significantly reduced in hypoxia whereas the W' parameter was not significantly altered. This supports the notion that CP is a parameter of oxidative metabolic function that is sensitive to manipulations in O_2 availability. We also found close agreement between the estimates of CP and W' obtained via conventional methods and the 3-min all-out test, both in normoxia and hypoxia. This provides further evidence that the all-out test is a valid single-visit method for assessing the P-D relationship. This is also the first study to demonstrate that relative changes in $CP/\dot{V}O_{2peak}$ are related to changes in the W' following an intervention. This finding questions the assumption that the W' represents a store of chiefly 'anaerobic' energy and instead suggests that it may define the range of power outputs between CP and $\dot{V}O_{2peak}$ within which fatigue accumulates commensurately with the development of the $\dot{V}O_2$ slow component.

Perspective 3

As expected, hypoxia caused marked reductions in both the CP and $\dot{V}O_{2max}$. Although these two parameters were reduced by hypoxia, the relative distance between the two parameters remained relatively similar and the W' was unaffected. However, there was considerable inter-individual variation in the responses of all three of these parameters as observed previously (Dekerle et al., 2012). Importantly, providing the all-out test resistance in hypoxia was set relative to physiological parameters obtained from ramp-incremental exercise in hypoxia, the 3-min test provided valid estimates of both CP and W' . This continues the thread of experimental chapters adding to the existing evidence of the 3-min all-out test providing valid and reliable CP and W' estimates. Additionally, the 3-min all-out test appears to provide reliable and valid CP & W' estimates in environments and under conditions designed to alter either the CP or W' . As such, the all-out test is indeed proving to be a practical and expeditious method of characterising the P-D relationship for severe-intensity exercise. As the test provides a practical tool with which to assess performance capabilities over durations spanning ~ 2 to 45 minutes, and sports performances over these durations are fiercely contested across multiple linear endurance events, inducing increases in either the CP, the W' or ideally both parameters would prove advantageous for exercise performance. Recently, repeated sprint interval training has proved very beneficial for severe-intensity exercise tolerance and ostensibly must enhance either the CP or the W' , or both. The 3-min all-out test should prove a very efficacious method of determining training-induced changes in the P-D relationship. Furthermore, if any dynamic exercise training method is to cause increases in the W' , sprint interval training should be a strong contender due to its 'anaerobic' demand and extreme- and severe-intensity nature.

Chapter 7 – Effect of 6-weeks of sprint-interval or endurance training on the power-duration relationship for severe-intensity exercise in humans

7.1. Introduction

Repeated sprint interval training (SIT) appears to be a potent stimulus for vascular and muscular adaptations similar to those observed with lower-intensity, continuous exercise. As such, SIT continues to receive considerable interest from both a clinical and exercise performance perspective, not least due to the substantially reduced time commitment for the health and performance benefits attained (Gibala & Jones, 2013). SIT typically comprises a number (~ 4 to 8) of short (20 s to 60 s), supra-maximal exercise bouts, interspersed with relatively large (2 to 5 min) active, or passive, recovery periods (Gibala & McGee, 2008). However, the majority of studies within the literature have investigated the efficacy of a 30 s sprint interval duration, and a ~ 4 to 5 min recovery. While our understanding of the acute (Little, Safdar, Bishop, Tarnopolsky, & Gibala, 2011) and chronic (Burgomaster et al., 2008) adaptations is developing, the exact mechanism(s) via which SIT enhances muscular endurance performance is currently illusive.

SIT requires ~ 10 % of the work done during 'typical' (~ 65 % $\dot{V}O_{2peak}$) endurance training to elicit similar or slightly better metabolic (Burgomaster et al., 2008) and exercise performance adaptations (Burgomaster et al., 2005; Gibala et al., 2006). Despite the supra-maximal nature of SIT, the consistently documented outcomes of such training are: (i) increases in oxidative enzyme activities (Burgomaster et al., 2008; Burgomaster et al., 2005; Gibala et al., 2006); (ii) up-regulation of 'oxidative' transcriptional proteins (Gibala, 2009; Gibala et al., 2009; Little et al., 2011; Little, Safdar, Cermak, Tarnopolsky, & Gibala, 2010a; Serpiello et al., 2012); and (iii) enhancements in severe-intensity exercise performance (Bailey et al., 2009b; Burgomaster et al., 2005; Gibala et al., 2006). Two of these previous investigations have both reported remarkable

improvements in severe-intensity exercise tolerance following just six sessions of SIT over a two-week period (Bailey et al., 2009b; Burgomaster et al., 2005). Bailey et al. (2009) report a 50 % increase in T_{lim} while Burgomaster et al. (2008) report a 100 % improvement in severe-intensity exercise tolerance following an almost identical training regime. From a bioenergetics perspective, these increases in severe-intensity exercise performance should be quantifiable based on alterations in the P-D relationship for severe-intensity exercise.

If severe-intensity exercise tolerance is to increase to the magnitudes reported following SIT, one of two changes must occur; 1) CP must increase or, 2) W' must increase. If CP increases, the demarcation between heavy-intensity exercise (sustainable) and severe-intensity exercise (unsustainable) increases. Therefore, at the same absolute (severe-intensity) power output, following an increase in CP, the energy deficit between CP (supply) and the imposed power (demand) has reduced. Assuming the W' is unchanged, T_{lim} will increase. Alternatively, if the CP remains unchanged but the W' increases in magnitude, the energy deficit between supply and demand remains unchanged, but a greater energy 'store' or supply is available to supplement the deficit; the predicted result of which would be an increased T_{lim} in the severe-intensity domain. It stands to reason that the performance improvements noted following SIT in Bailey et al. (2009) and Burgomaster et al. (2008) must have resulted in an increase in the participants' CP, W' or both.

The advent of a single, all-out, maximal exercise test to estimate CP and W' has substantially expedited the study of the P-D relationship. Burnley et al. (2006) first introduced the 3-min all-out cycling test as a valid measure of the CP. The test has since received much attention, proving to be a valid measure of the W' also (Vanhatalo et al., 2007, 2008a, 2008b). The premise behind the all-out test is that when maximal exercise is initiated and continued for 3 minutes, the W' will be expended from the initiation of the test, causing power output to decrease precipitously in a fashion resembling a hyperbola. As the power output begins to reach a steady-state or 'asymptote', logically the W' has been fully expended, with the resulting power output representing the maximal ATP turnover via sustainable, oxidative means; the CP. For clarity different terminology is used to describe P-D parameters from the all-out test; the

asymptotic power over the final portion of the test is termed 'end power' (EP). The W' equivalent thus represents the sum of 'work performed above end power' (WEP).

Currently, there is little evidence that the W' parameter of the P-D relationship is malleable. It appears to be unaltered by nutritional supplementation with NaHCO_3 (Vanhatalo et al., 2010b), creatine (Vanhatalo & Jones, 2009a), or nitrate (Kelly, Vanhatalo, Wilkerson, Wylie, & Jones, 2013) nor subsequent to 'endurance training' (Gaesser & Wilson, 1988; Jenkins & Quigley, 1992; Poole et al., 1990; Vanhatalo et al., 2008a) but may be enhanced with larger muscle cross sectional area (Miura, Endo, Sato, Barstow, & Fukuba, 2002) or resistance training (Sawyer et al., 2014). The one dynamic exercise (cycling) training study demonstrating a change in the W' comes from a training methodology akin to SIT (Jenkins & Quigley, 1993). However, the interval duration of this investigation was 60 s with 5 min passive recovery, an increase in interval duration of 100 % over that employed more recently by both Bailey et al. (2009) and Burgomaster et al. (2005). With a reduction in interval duration, the relative contribution of anaerobic ATP provision increases (Withers et al., 1991). Therefore, potentially, enhancements in severe-intensity exercise performance following 30 s SIT may come as a direct result of an increased W' despite the numerous reported benefits of SIT for 'aerobic' indicators of muscle and vascular function.

The purpose of the present investigation was to ascertain the effect of SIT compared to more conventional 'endurance' (END) training on the parameters of the P-D relationship for severe-intensity exercise. In addition to the conventional determination of CP and W' , the 3-min all-out test was employed as a practical method of elucidating changes in the P-D relationship. Furthermore, a comparison of SIT vs. END was attempted in an effort to provide practical advice as to which training method is most likely to be beneficial in altering various physiological parameters linked to exercise performance. It was hypothesised that SIT would illicit similar physiological adaptations to non-work matched END training. However, SIT was expected to cause an increase in the W' and the CP parameter of the P-D relationship, whereas END was expected to increase CP only, possibly at the expense of the magnitude of the

W' . As has been reported previously, the 3-min all-out test was expected to provide valid and reliable estimates of CP and W' when compared with the conventional determination of these parameters. Furthermore, $\dot{V}O_{2\max}$ was expected to increase only in the SIT group while GET was expected to increase in both groups following the training period.

7.2. Methods

7.2.1. Participants

Fifteen healthy, recreationally active males ($n = 8$: 22 ± 4 yr, 1.78 ± 0.06 m, 78.9 ± 9.6 kg) and females ($n = 7$: 24 ± 6 yrs, 1.65 ± 0.06 m, 62.9 ± 5.0 kg) volunteered and provided written informed consent to participate in this study, which received ethical approval from the local ethical research committee. Preliminary health checks were conducted to ensure all participants were free from risk factors for cardiovascular or metabolic disease and otherwise deemed safe to participate in a new exercise regime. Participants were instructed to report to the laboratory in a well-hydrated state, having avoided exhaustive exercise and alcohol for at least 24 hours, caffeine for 3 hours and food for 2 hours prior to each testing occasion.

7.2.2. Pre-training assessments

$\dot{V}O_{2peak}$ and GET

See section 3.4 for details.

7.2.3. CP and W'

On three separate occasions each participant cycled to the limit of tolerance at a power output chosen to elicit exhaustion within the range of 3 to 12 minutes (Bishop et al., 1998; Poole et al., 1990; Vandewalle et al., 1997). The time to exhaustion (T_{lim}) of each of these severe-intensity bouts was used to determine CP and W' parameters via the conventional work-time and power vs. $1 \cdot \text{time}^{-1}$ models. Exhaustion was assumed using the same criteria as for the incremental test.

7.2.4. EP and WEP

The fourth and fifth visits to the laboratory required participants to complete a 3-min all-out cycling test for the determination of EP and WEP. See section 3.6 for details.

7.2.5. Pairing

Participants were paired according to closely matching CP/EP and W/WEP parameters. As these parameters were the dependant variables of interest, it was necessary to ensure each group was closely matched for both parameters pre-training. One participant from each pairing was randomly allocated to the SIT group, with the other participant joining the END group. The remaining participant (who matched least-well with any other participant) was allocated to the SIT group.

7.2.6. Training protocol

Several days after the final pre-training assessment, the training protocol began. Both the SIT and END groups visited the laboratory three times per week for 6 weeks (18 training sessions). The SIT group completed 30 s all-out cycling bouts separated by 4.5 min of pedaling against 50 W (to help alleviate light-headedness and nausea). In weeks 1 and 2, four 30 s bouts were completed per session, increasing by an additional 30 s bout every two weeks (see Figure 7.1 p153). The resistance on the ergometer was set according to each individual's performance during the 3-min all-out test. A larger resistance was set on the ergometer so that at 80 % of peak cadence attained during the 3-min all-out test, PPO from the all-out test would be attained. Thus, participants were able to attain a higher PPO during the 30 s sprint intervals than they could during the 3-min all-out test.

The END group completed constant-power cycling at a power output equivalent to 50 % of the difference between GET and EP ($50 \% \Delta 2$). In weeks 1 and 2 participants completed 30 minutes, adding an additional 10 minutes duration every two weeks (see Figure 7.1 p153). Following the completion of 9 training sessions, all participants completed a ramp-incremental and 3-min all-out test to

enable training intensities to be re-adjusted. Following the completion of all 18 training sessions, participants were given eight days rest before reporting to the laboratory to repeat each of the pre-training tests. The duration between final training session and the start of the post-training testing battery was determined based on the impulse-response model of training adaptation for the SIT group. As this group provided a measure of maximal performance capability from every training session it was possible to model the expected ‘fatigue’ and ‘freshness’ response to the completed training and subsequent removal of that training impulse. Eight days following the final training session should have resulted in participants (of the SIT group at least) returning for post-training tests in a recovered but not ‘detrained’ state (Clarke & Skiba, 2013).

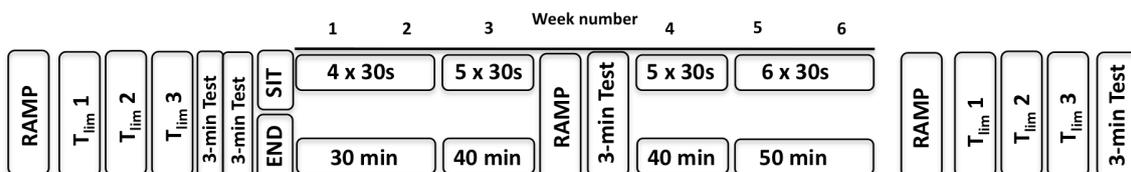


Figure 7.1. Schematic of experimental design.

Schematic of the general testing and training schedule employed in the present study. T_{lim} 1 – 3 indicate severe-intensity work bouts to the limit of tolerance where time to exhaustion and constant-power were recorded to inform the linear work-time and power vs. 1.time⁻¹ power-duration relationships.

7.2.7. Statistical analysis

Training effects

Pre- and post-training parameters within each training group were analysed using paired-samples t-test. Change scores for parameters across training groups were analysed using independent-samples t-test. In addition, magnitude based inferences were completed for each parameter using the method of Batterham & Hopkins (2006). For detailed explanation of this method, please see (Hamilton, Paton, & Hopkins, 2006), but briefly, first, the smallest change in a parameter deemed worthy of exhibiting a positive or negative effect on human performance was stated – known as the ‘smallest worthwhile change’ (SWC). Second, the mean percent change in a parameter and the 90 % confidence interval (CI) around that mean change was determined. Lastly, based on the effect size (magnitude) of the change observed, the confidence interval around that mean change and the SWC, inferences are made based on

likelihood outcomes of the intervention being positive (+ve), trivial or negative (-ve) for a given parameter or exercise performance. For example, while a 0.4 % reduction in performance time will result in one additional win for every 10 races (Hopkins, 2004), this 0.4 % change in performance time up scales to a required 1 % change in cycling power output for events over 1 to 40 km (Paton & Hopkins, 2001). 1 % was also deemed the SMC for all power measurement parameters and total work done for the 3-min all-out test. Over an endurance event lasting between 4 to 5 minutes (i.e. 4 km pursuit), a 1 kJ increase in W' would result in a ~1 % change in power output, thus the SWC percentage for W' was determined based on pre-training W' magnitudes (7 %). For measurements of oxygen consumption, a conservative SWC of 2.5 % was used (Pelletier, Lacerte, & Goulet, 2013). All qualitative inferences, 90 % CI and percent likelihood figures were generated using a publicly available spreadsheet (Hopkins, 2003).

Validity of all-out test

Comparisons between conventionally-derived P-D parameters, CP and W' , 3-min-derived P-D parameters, EP and WEP and ramp- and 3-min-derived $\dot{V}O_{2peak}$ measurements were initially analysed using paired-samples t-tests (independent of training group) before investigating the validity of the all-out (practical) measures against the conventional (criterion) measures using linear regression (Hopkins, 2000). The linear regression method provides (i) a calibration equation for the practical measure to bring the results into line with the criterion, (ii) a TE of the practical measure and (iii) a measure of how 'good' the practical measure is (the correlation coefficient; (Hopkins, 2010)). Where appropriate, log transformations were made to better-fit data to a linear function. Back-transformations were conducted with % values presented only in these cases. Elsewhere, unless otherwise stated, values are mean \pm SD.

7.3. Results

7.3.1. Comparison of SIT and END training

Training was very well adhered to. The END group completed 100 % of the prescribed training. The SIT group completed 99.3 % of the prescribed training, with the deviation from 100 % being due to a single incidence of vomiting following the third 30 s interval during session 1 for one participant. The END training group completed significantly more work than the SIT group over the first 9 sessions (2412 ± 477 vs. 589 ± 153 kJ respectively, $P < 0.001$), the last 9 training sessions (3726 ± 609 vs. 849 vs. 214 kJ respectively, $P < 0.001$) and the entire duration of the training intervention (6138 ± 1077 vs. 1438 ± 367 kJ respectively, $P < 0.001$; Figure 7.2 p155). The END group trained at a significantly lower intensity compared with SIT for the duration of the training intervention (mean intensity relative to EP: 80 ± 5 vs. 285 ± 20 % respectively, $P < 0.001$; Figure 7.2 p155).

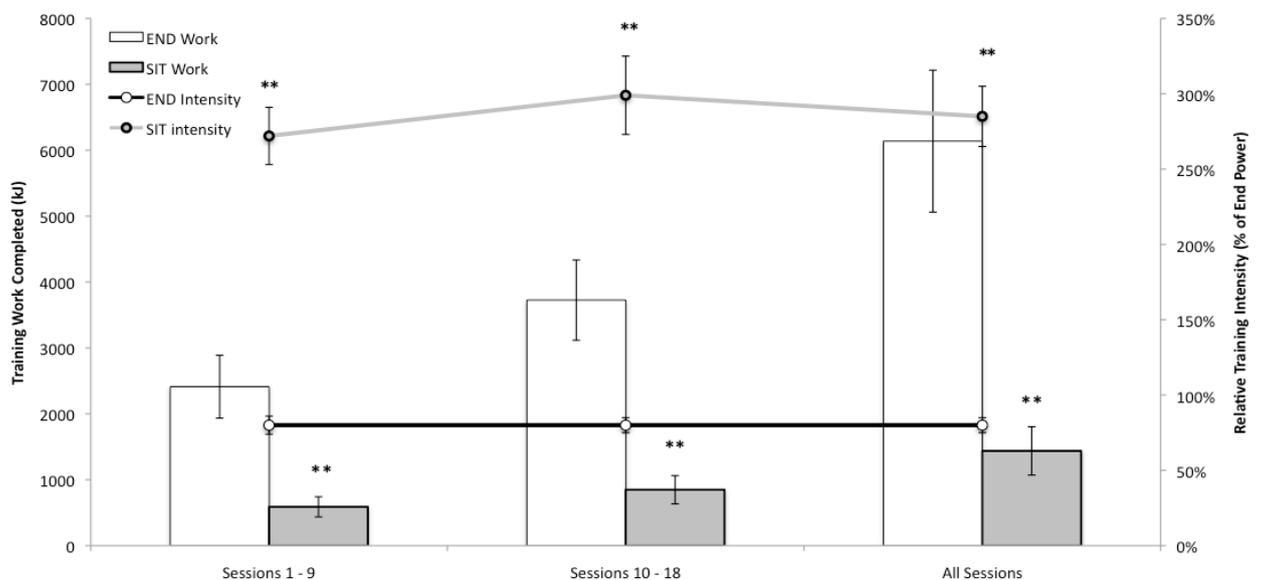


Figure 7.2. SIT and END training volume and intensity comparison.

Mean work completed during training by END and SIT groups and relative intensity of the work completed (relative to end power of 3-min all-out test). ** denotes a significant difference compared to END group ($P < 0.001$). SIT work consists only of the 30 s sprint intervals.

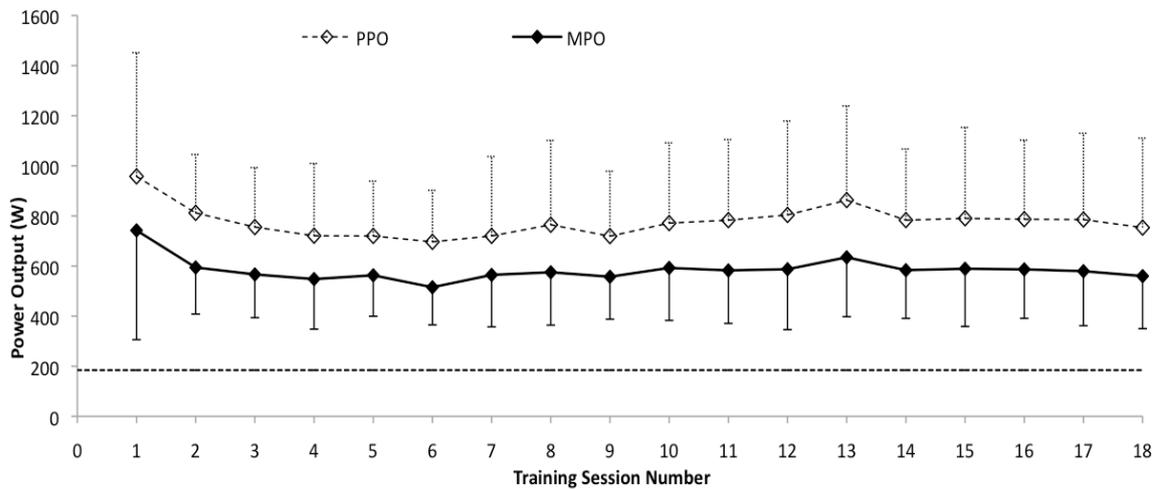


Figure 7.3. SIT group mean training performances over training period.

SIT group highest mean (\pm SD) training performances per session; open symbols depict maximum peak power output (PPO) of every training session. Closed symbols depict maximum mean power output (MPO) for a single 30 s effort for each training session. The horizontal dashed line represents SIT group pre-training all-out EP. There was no change in either PPO or MPO over the training duration ($P > 0.05$).

There were no differences in the duration of severe-intensity exercise bouts performed pre- and post-training for the determination of CP and W' (see Figure 7.4 p159). There were also no differences in cadence profiles (peak cadence, average cadence or end-cadence) between pre- and post-training 3-min all-out tests. The END training group displayed significant changes in CP (18 ± 14 %), EP (17 ± 11 %), P_{ramp} (9 ± 7 %), GET_W (23 ± 13 %), $GET_{L,\text{min}}$ (19 ± 12 %), 3-min PPO (12 ± 5 %), 3-min $\dot{V}O_{2\text{peak}}$ (5 ± 3 %) and total work done during 3-min all-out test (11 ± 7 %) over the training period; W' (-9 ± 21 %), WEP (1 ± 8 %) and $\dot{V}O_{2\text{peak}}$ (7 ± 8 %) did not alter (Table 7.1 p157 & Table 7.2 p158). The SIT group displayed significant changes in CP (12 ± 9 %), $\dot{V}O_{2\text{peak}}$ (10 ± 8 %), 3-min $\dot{V}O_{2\text{peak}}$ (6 ± 7 %), GET_W (21 ± 13 %) and $GET_{L,\text{min}}$ (15 ± 8 %) over the training period; no changes were observed in EP (-0 ± 9 %), W' (5 ± 25 %), WEP (11 ± 15 %), P_{ramp} (5 ± 8 %), 3-min PPO (6 ± 7 %) or 3-min all-out total work done (3 ± 9 % see Table 7.1 p157 & Table 7.2 p158). The only parameter to change differently between training groups over the duration of the study was EP from

the 3-min all-out test (Table 7.2 p158). Changes in all other parameters did not differ between training groups (Table 7.2 p158). Table 7.2 p158 presents a practical tool for comparing the effects of the two training regimes.

Table 7.1. Pre- and post-training group mean values (\pm SD).

	END		SIT	
	Pre	Post	Pre	Post
Critical Power (W)	185 \pm 44	217 \pm 42*	194 \pm 52	214 \pm 47*
3-min End Power (W)	169 \pm 37 ^a	197 \pm 44* ^a	184 \pm 42	183 \pm 37 ^a
W' (kJ)	14.7 \pm 6.0	13.6 \pm 6.6	16.5 \pm 4.5	15.8 \pm 5.2
3-min WEP (kJ)	15.4 \pm 3.1	15.6 \pm 3.5	15.7 \pm 5.9	17.0 \pm 4.6
VO _{2peak} (L.min ⁻¹)	3.18 \pm 0.63	3.42 \pm 0.73	3.35 \pm 1.02	3.63 \pm 0.88*
3-min VO _{2peak} (L.min ⁻¹)	3.09 \pm 0.55	3.26 \pm 0.67*	3.34 \pm 0.98	3.50 \pm 0.82* ^a
P _{ramp} (W)	273 \pm 52	299 \pm 63*	286 \pm 74	297 \pm 62
GET (L.min ⁻¹)	1.51 \pm 0.36	1.79 \pm 0.48*	1.74 \pm 0.49	1.99 \pm 0.55*
GET (W)	99 \pm 22	123 \pm 34*	108 \pm 30	131 \pm 36*
3-min PPO (W)	590 \pm 138	665 \pm 173*	673 \pm 199	710 \pm 208
3-min Total Work (kJ)	45.8 \pm 7.5	51.0 \pm 10.0*	48.9 \pm 12.9	49.9 \pm 10.4

* denotes a difference to pre-training value ($P \leq 0.05$).

^a denotes a significant difference between the all-out parameter and the conventionally-derived equivalent parameter presented directly above ($P \leq 0.05$).

Table 7.2. Comparison of SIT Vs. END for altering measured parameters.

Percent change scores and difference in change scores between training interventions. A qualitative statement about which training technique to employ based on the likelihood/odds ratios is provided. The percentage change deemed 'worthwhile' in each of the parameters is presented, justification for these values is provided within the methods section.

	% change in parameter			% chance 'true' change is practically -ve/Trivial/+ve	Qualitative inference	Smallest worthwhile change (%)
	END Mean \pm SD	SIT Mean \pm SD	Difference \pm 90% CI			
Critical Power	18 \pm 14	12 \pm 9	-6 \pm 11	80/8/12	Use END	1
End Power	17 \pm 11	-0 \pm 9*	-15 \pm 9	99/0/0	Use END	1
3-min PPO	12 \pm 5	6 \pm 7	-6 \pm 6	94/4/2	Use END	1
3-min total work done	11 \pm 7	3 \pm 9	-7 \pm 7	93/4/3	Use END	1
P _{ramp}	9 \pm 7	5 \pm 8	-4 \pm 7	80/11/9	Use END	1
GET _W	23 \pm 13	21 \pm 13	-2 \pm 12	57/11/31	Use either END or SIT	1
VO _{2peak}	7 \pm 8	10 \pm 8	3 \pm 8	12/37/51	Use SIT	2.5
3-min Peak VO ₂	5 \pm 3	6 \pm 7	1 \pm 5	10/57/33	Use either END or SIT	2.5
GET _{L,min}	19 \pm 12	15 \pm 8	-3 \pm 10	57/29/14	Use END	2.5
W'	-9 \pm 21	-5 \pm 25	4 \pm 21	16/43/41	Use SIT	7
WEP	1 \pm 8	11 \pm 15	10 \pm 11	1/32/67	Use SIT	7

* denotes a significant difference compared with percent change score of END group (P < 0.05)

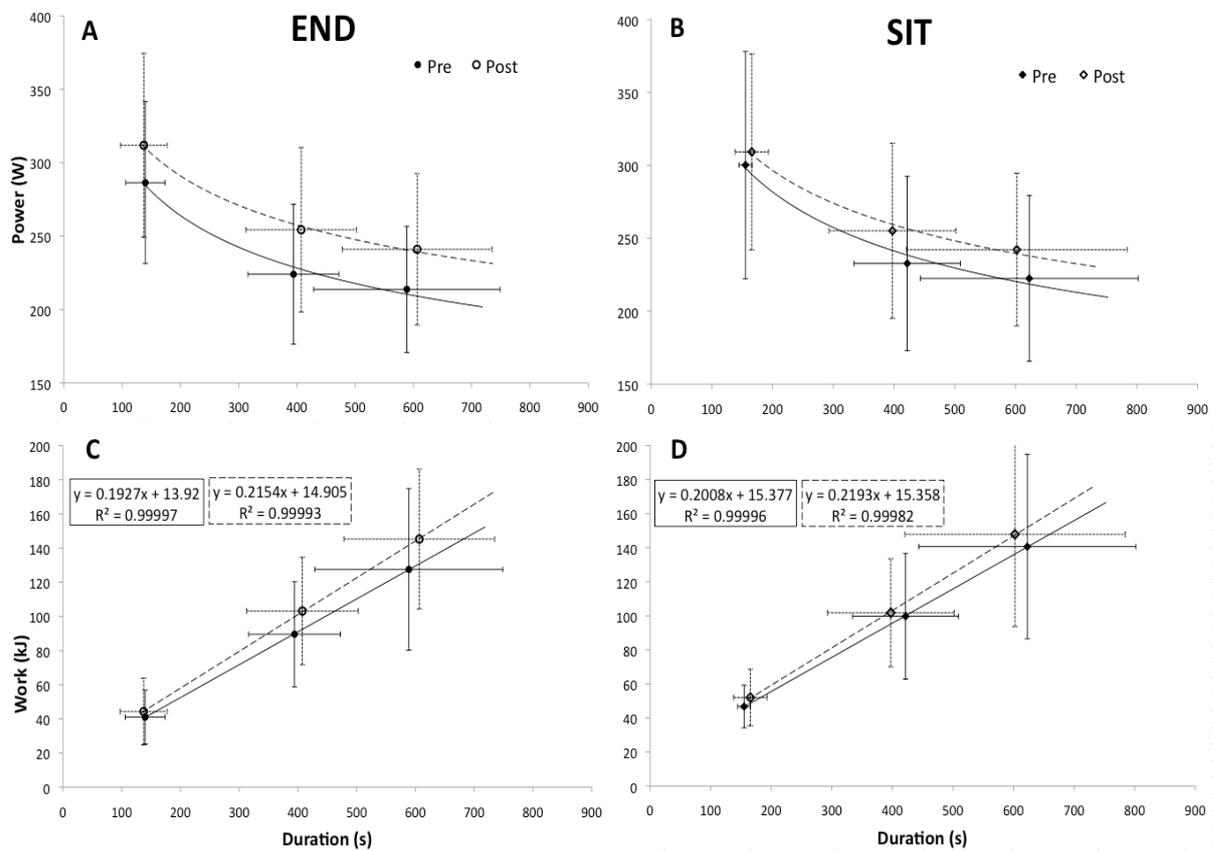


Figure 7.4. Conventional P-D and work vs. time relationships pre- and post-training.

Power-duration relationships for END and SIT groups (panels A and B respectively) pre- and post-training and the corresponding transformations via the linear work-time models (panels C and D). Solid Symbols and solid lines represent pre-training values and relationships with open symbols and dashed lines represent post-training values.

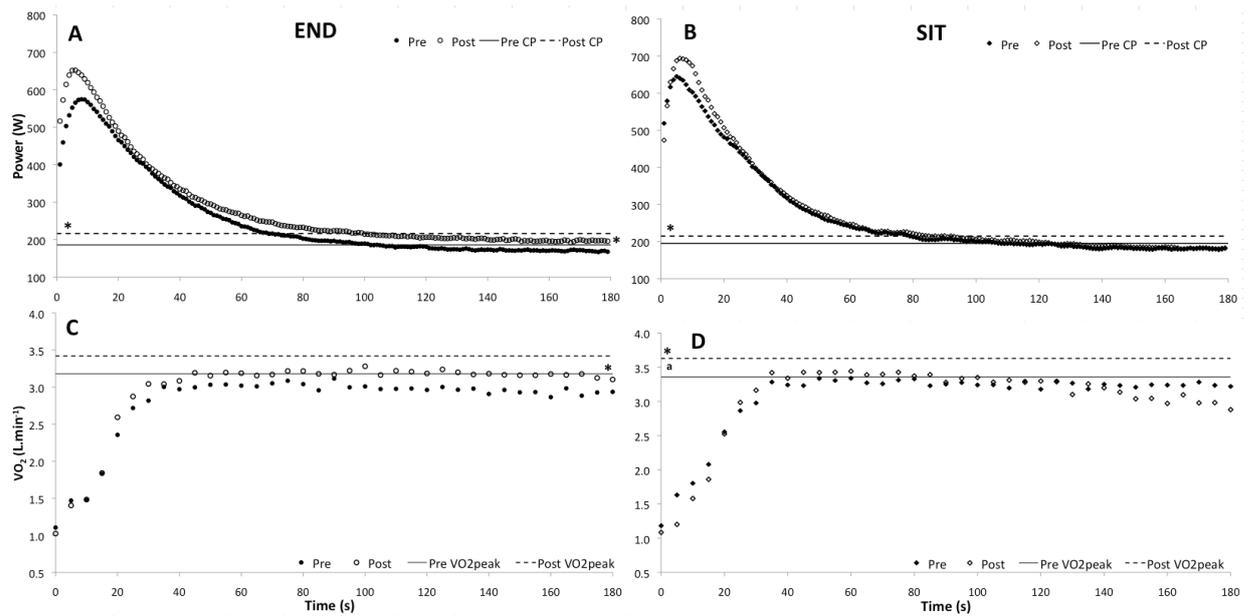


Figure 7.5. Mean 3-min power and $\dot{V}O_2$ responses pre- and post-training. Group mean 3-min all-out power (panels A and B) and $\dot{V}O_2$ (panels C and D) profiles of END (panels A and C) and SIT (panels B and D) pre- and post-training. Solid horizontal lines represent conventionally derived pre-training parameter values (CP in panels A and B; $\dot{V}O_{2peak}$ in panels C and D). Dashed horizontal lines represent the post-training equivalents. * and ^a denote the significant differences as outlined in Table 7.1 p157; briefly, in the END group, CP and EP both increased over the training period and 3-min all-out $\dot{V}O_{2peak}$ also increased post-training. In the SIT group, CP and $\dot{V}O_{2peak}$ significantly increased, with $\dot{V}O_{2peak}$ from the all-out test post-training being significantly different to ramp-determined $\dot{V}O_{2peak}$.

7.3.2. Comparisons of conventional and all-out estimations

As depicted in Figure 7.6 p162, the 3-min all-out test routinely underestimated CP (mean difference or mean bias (\pm 90 %CI) -19 ± 6 W), concomitantly overestimated W' (0.71 ± 0.98 kJ) and slightly underestimated $\dot{V}O_{2peak}$ (-0.10 ± 0.07 L·min⁻¹). The TE of EP, WEP and 3-min $\dot{V}O_{2peak}$ are 19 ± 9 W, 3.2 ± 1.5 kJ and 0.23 ± 0.11 L·min⁻¹ respectively. However, as depicted in panel A of Figure 7.6 p162 and in Table 7.1 p157, the post-SIT EP data is statistically different to CP, whereas pre-SIT there was no (statistical) difference between EP and CP. A significant correlation was found between the difference in ramp-derived and all-out-derived $\dot{V}O_{2peak}$ and the difference between CP and EP ($r = 0.471$, $P = 0.012$).

Table 7.3. Conventional and all-out parameter data, pre- and post-training. Comparison of conventional and all-out parameters for all participants pre- and post-training and change scores in parameters.

	Conventional	All-Out	P-Value
Pre CP/EP (W)	190 ± 47	177 ± 39*	0.001
Post CP/EP (W)	216 ± 43	189 ± 39*	0.001
Change score CP/EP (W)	26 ± 18	12 ± 23*	0.020
Pre W'/WEP (kJ)	15.7 ± 5.2	15.6 ± 4.6	0.909
Post W'/WEP (kJ)	14.8 ± 5.8	16.3 ± 4.1	0.059
Change score W'/WEP (kJ)	-0.9 ± 3.1	0.8 ± 2.0	0.067
Pre VO _{2peak} /Peak VO ₂ (L.min ⁻¹)	3.28 ± 0.84	3.22 ± 0.79	0.449
Post VO _{2peak} /Peak VO ₂ (L.min ⁻¹)	3.53 ± 0.79	3.39 ± 0.74*	0.014
Change score VO _{2peak} /Peak VO ₂ (L.min ⁻¹)	0.25 ± 0.23	0.16 ± 0.16	0.164

* denotes a statistical difference compared with corresponding conventional parameter.

P values are presented to enable personal interpretation.

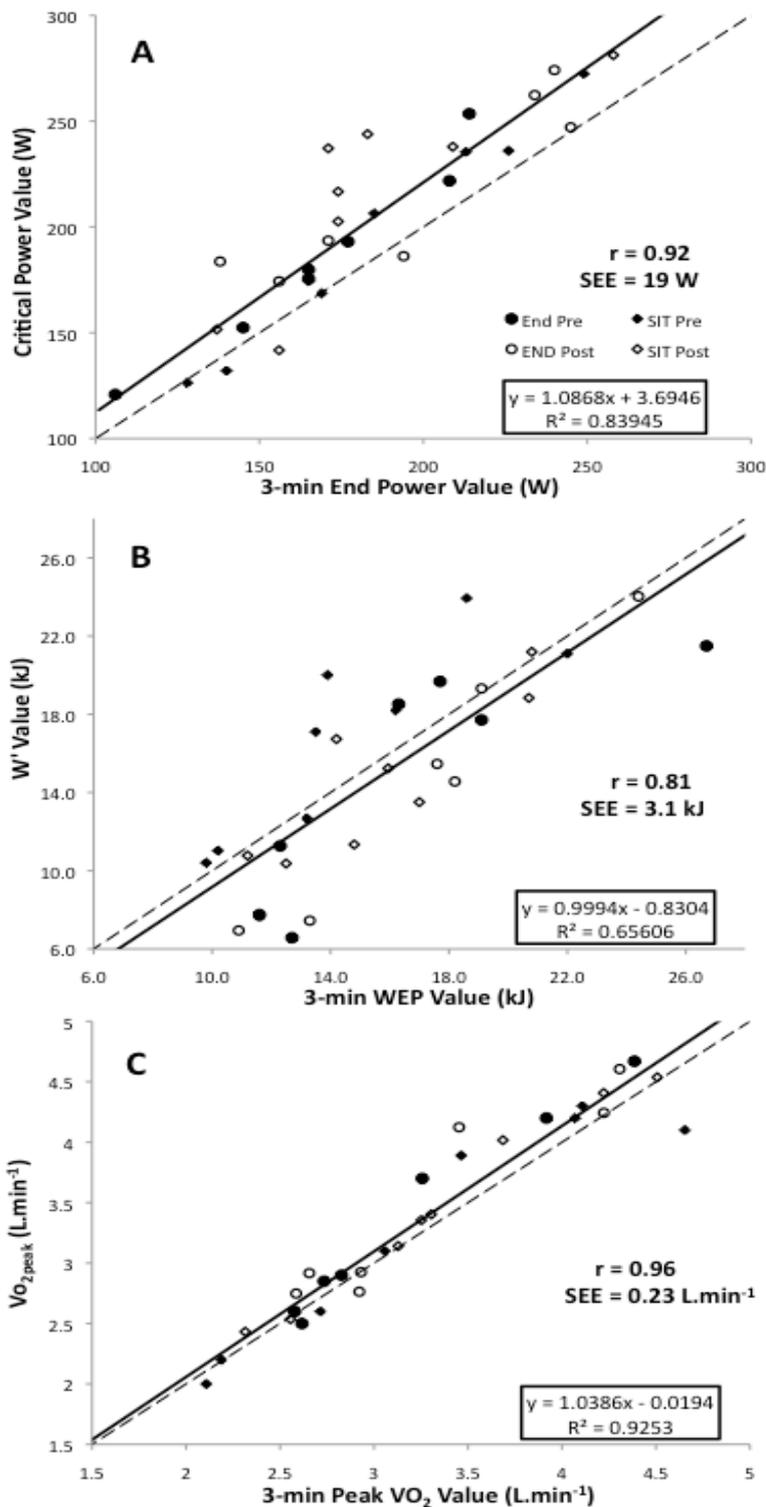


Figure 7.6. Linear regression of all-out vs. conventional parameters. Regression plots of all-out-derived parameters against conventionally-derived parameters. Although groups (END & SIT) and time points (pre- & post-training) are depicted, all data was used in generating the regression in each case. The solid black line represents the linear line of best fit. The dashed line provides the line of identity. The calibration equation and R^2 for each regression is provided in each panel.

7.4. Discussion

The principal novel finding of the present study was that low volume, supra-maximal SIT alters the P-D relationship of severe-intensity exercise similarly to more conventional END training over a 6-week period in healthy humans. The CP increased in both END and SIT groups with no discernible change in the W' . The notable increase in CP and robustness of the W' in response to training is similar to the existing literature examples that have explored the trainability of the P-D parameters (Gaesser & Wilson, 1988; Jenkins & Quigley, 1992; Poole et al., 1990; Vanhatalo et al., 2008a). The all-out test parameters, however, were not (statistically) similar to the conventional CP and W' parameters. That is, EP was significantly lower than CP both pre- and post-training in both groups. WEP was not significantly different to W' pre or post training, but trended toward significance following the training intervention ($P = 0.059$; Table 7.3 p161). Furthermore, the WEP change score (Table 7.3 p161) moved in a positive direction, whereas the change in W' was negative (again, the mean difference showed a trend toward significance, $P = 0.067$). For clarity, these results will be discussed in two sections; (i) the effect of END and SIT on the conventionally derived P-D parameters; (ii) the difference in parameter estimates between conventional and all-out methods.

7.4.1. Training-induced alterations in the conventionally derived P-D relationship
Historically the CP parameter can be increased by both sustained low-intensity training or by shorter duration, high-intensity interval exercise (Gaesser & Wilson, 1988; Jenkins & Quigley, 1992; Poole et al., 1990; Vanhatalo et al., 2008a). Previously, the shortest training work-interval employed to alter the P-D relationship was 60 s, resulting in a change in the W' but not the CP (Jenkins & Quigley, 1993). In contrast, the present study demonstrates that 18 sessions of repeated supra-maximal, 30 s, all-out cycling bouts (totaling 45 min of all-out effort) resulted in similar increases in CP as observed following longer duration (720 min) heavy-intensity cycling. Contrary to our hypothesis, the W' parameter was unaffected by SIT.

In the present study, the intensity of P-D predicting trials both pre-and post-training were based upon incremental exercise performance and as such, the

duration of predicting trials were similar before and after the training period (Figure 7.4 p159). It is important to point out that the duration of the predicting trials used has a profound effect on the parameter estimates of CP and W' (Bishop et al., 1998; Vandewalle et al., 1997). Utilising short-duration predicting trials, leads to an over-estimation of the CP and an under-estimation of the W' ; while utilising only long-duration predicting trials has the reverse effect on the parameter estimates, irrespective of model fit. Furthermore, durations of P-D predicating trials of less than 3 minutes risk not enabling the full utilisation of the W' prior to exhaustion (Bishop et al., 1998). Conversely, predicting trials that surpass ~ 15 min begin to become affected by motivation and/or central-fatigue (Abbiss & Laursen, 2005; Amann, 2011), which may 'contaminate' the quantification of peripheral muscle fatigue. Unfortunately, some of the existing literature investigating the change in the P-D relationship with training falls short of these guidelines. Jenkins & Quigley (1993) made no adjustment to the intensity of the predicting trials performed pre- and post-training. Pre-training, the predicating trials were all short-duration (all trials shorter than 250 s). Post-training, T_{lim} was appreciably longer (longest trials lasting ~ 325 to 375 s). This will have contributed to the reported 50 % improvement in the W' . In the present study the mean differences between durations of predicating trials was 10 ± 54 s for the END group and -12 ± 63 s for the SIT group; minimising any effects of trial duration on CP and W' parameter estimates (see Figure 7.4 p159). Combined with the very high coefficient of model fit for both groups (pre and post; R^2 of 0.999 for both END and SIT; Figure 7.4 p159 Panels C and D respectively), the conventional CP and W' parameter estimates appear valid. It is clear that SIT is effective at increasing the CP parameter. In contrast to our hypothesis, the W' parameter was unaffected by SIT. This result brings into question the conclusions of Jenkins & Quigley (1993) due to the similarity in training structure with the present study (short-duration, supra-maximal training interspersed with ~ 5 minutes of recovery). Our findings add further support to the existing literature which has shown that the CP is altered with intense and sub-maximal exercise training with no change in the W' (Gaesser & Wilson, 1988; Jenkins & Quigley, 1992; Poole et al., 1990; Vanhatalo et al., 2008a).

While the exact origin(s) of the observed increase in CP remains to be elucidated, the available evidence suggests an increased number and function

of mitochondria to be a likely candidate (Burgomaster et al., 2008; Coffey & Hawley, 2007; Gibala, 2009). PGC-1 α (the transcriptional co-activator of mitochondrial biogenesis) mRNA expression is acutely increased following one session (four 30 s maximal sprints) of SIT (Gibala et al., 2009). Over time (two to six weeks), with repeated SIT (and END) stimuli, the PGC-1 α and PDH protein content is increased along with the activities of citrate synthase (CS), COX II & IV and β -HAD. While combined, these inherently aerobic adaptations don't consistently result in an increase in the $\dot{V}O_{2peak}$ (Gaesser & Wilson, 1988; Poole et al., 1990) they do contribute to increasing the LT (Gaesser & Wilson, 1988), GET (Bailey et al., 2009b) and now, the CP; all of which are sub-maximal parameters linked to endurance performance (Gaesser & Wilson, 1988; Poole et al., 1988; Poole et al., 1990). Furthermore, there is some evidence that SIT may enhance muscle O₂ extraction, which in turn may speed the kinetics of $\dot{V}O_2$ (Bailey et al., 2009b). While Bailey et al. (2009) compared SIT to a work-matched, moderate-intensity training group, it is reasonable to assume a similar adaptation may occur in response to heavy-intensity training due to the resounding similarity in aerobic adaptations which occur in response to both SIT and heavy-intensity 'endurance' training (Burgomaster et al., 2008; Gibala et al., 2006).

'Anaerobic' adaptations to training have received comparatively little attention compared to 'aerobic' adaptations. While our results add to the paucity of evidence of the W' increasing in magnitude subsequent to an intervention, there is some evidence that biochemical and histochemical markers of anaerobic potential do alter with 'anaerobic' training. Glycogen synthase, phosphorylase, phosphofruktokinase, lactate dehydrogenase, pyruvate kinase and hexokinase have all been shown to exhibit greater activity following 'sprint' training interventions (Cadefau et al., 1990; Dawson et al., 1998; Jacobs et al., 1987; MacDougall et al., 1998; Parra, Cadefau, Rodas, Amigo, & Cusso, 2000; Roberts et al., 1982). There is some evidence that muscle fibre composition shifts toward a more type II dominated histochemistry, particularly following short-duration (< 10 s) sprint training (Dawson et al., 1998; Jansson, Esbjornsson, Holm, & Jacobs, 1990). However, the predominance of the evidence suggests that proportions of type IIb fibres only reduce with training (both sprint and endurance), with type IIa fibres exhibiting the ability to alter

their myosin heavy chain isoforms in either direction (slow type I ← fast oxidative type IIa → fast type IIb/IIx), which is likely the stimulus for the compensatory adjustment in the proportion of type I fibres (Allemeier et al., 1994; Esbjornsson, Hellsten-Westing, Balsom, Sjodin, & Jansson, 1993a; Jacobs et al., 1987). While these potential alterations within the trained muscle of participants who completed the present study cannot be confirmed or denied, 'anaerobic' capabilities (the *W'*) were assessed, which presumably should reflect any such alterations in muscle phenotype or biochemistry. However measurement of 'anaerobic' performance remains somewhat equivocal (Allemeier et al., 1994; Cadefau et al., 1990; Dawson et al., 1998; Esbjornsson et al., 1993a; Jacobs et al., 1987; Jansson et al., 1990). What is clear is an increased ability of the untrained muscle to store glycogen following 30 s SIT (Burgomaster et al., 2008; Gibala et al., 2006) and increases in enzyme activities involved in glycolysis (Burgomaster et al., 2008; Dawson et al., 1998; Hellsten-Westing, Balsom, Norman, & Sjodin, 1993; Linossier, Denis, Dormois, Geysant, & Lacour, 1993). However, the expected greater glycolytic capacity doesn't appear to consistently translate to a performance improvement in highly glycolytic tasks ((Burgomaster et al., 2005; MacDougall et al., 1998) - first 30 s interval unchanged; (Allemeier et al., 1994; Esbjornsson, Sylven, Holm, & Jansson, 1993b; Jacobs et al., 1987; Jansson et al., 1990) - males), perhaps because of the muscle's apparent lower reliance on muscle glycogen during all-out 30 s cycle ergometry following SIT (Burgomaster et al., 2008). These factors, combined with the difficulty of reliably measuring 'anaerobic capacity', be it *W'* (CV 8 % (Vanhatalo, 2008)), MAOD (not a reliable measure; (Docherty, Smith, & Schroder, 2000; Noordhof, de Koning, & Foster, 2010)), or a mechanical performance test i.e. the *WaT* (not of sufficient duration to maximally expend 'anaerobic capacity'; (Vandewalle, Peres, & Monod, 1987; Withers et al., 1991)), may result in the lack of a measurable training response in the 'anaerobic' component of human performance. It could however, suggest that the human anaerobic system 'size' or 'magnitude' is not particularly malleable, which would appear to globally be the case (Gaesser & Wilson, 1988; Jenkins & Quigley, 1992; Poole et al., 1990; Vanhatalo et al., 2008a).

Our data suggests that the *W'* is not altered with either END or SIT training. However, the CP (from the conventional determination) is enhanced similarly

with either training regime. As such, it would appear that the improved exercise tolerance and performances observed elsewhere (Bailey et al., 2009b; Burgomaster et al., 2005) following SIT are a result of enhanced aerobic capabilities, not through increases in anaerobic capabilities, as would reasonably be predicted. Assuming the CP of the subjects of Bailey et al. (2009) occurred at 50 % Δ (\sim 213 W pre SIT, \sim 221 W post SIT), the change in T_{lim} (some 374 s) equates to a pre and post training W' of 18.9 and 20.4 kJ respectively. Therefore in that study the 50 % improvement in T_{lim} can be explained by a conservative 4 % change in CP, with no change in W' . In Burgomaster et al. (2005) where a 100 % improvement in T_{lim} was reported, it is not as easy to estimate the starting and ending CP value as the GET is not reported. Furthermore, the intensity of the T_{lim} trial was set at a workload eliciting 80 % of pre-training $\dot{V}O_{2peak}$. Gaesser & Wilson (1988) report that CP occurred at 83 % $\dot{V}O_{2peak}$ in their research participants. The present study, along with Gaesser & Wilson (1988), Poole et al. (1990), Vanhatalo et al. (2008) and Jenkins & Quigley (1992) all show that the fractional utilisation of $\dot{V}O_{2peak}$ at which CP occurs is increased following training. In the present study pre-training, both groups' CP workload occurred at \sim 68 % of P_{ramp} . Post-training this had increased to \sim 73 % P_{ramp} . Had we included a T_{lim} trial at 70 % of P_{ramp} pre- and post-training (even if we adjusted the post-training workload), we would have observed marked differences in T_{lim} due to the post-training T_{lim} workload being below the CP, and therefore with the heavy-intensity domain (Whipp & Ward, 2009).

7.4.1. 3-min all-out test parameters

This is the first example from our laboratory of the 3-min all-out test not providing similar P-D parameters to the conventional values of CP and W' . The END group's all-out EP parameter was \sim 20 W lower than the CP parameter both pre- and post-training. The EP for this group may not be valid, but it was reliable and the present study is the second example of the all-out EP providing a reliable estimation of CP following 'typical' endurance training (Vanhatalo et al., 2008a). The all-out WEP parameter from the END group was consistent with the magnitude of the W' both pre- and post-training. However, the all-out test results from the SIT group exhibit an interesting characteristic; while pre-

training the all-out parameters mimic the all-out response observed in the END group (~ 20 W under-estimation of CP and a WEP similar to W'), post-training the response of all-out EP parameter from the SIT group differs considerably to the conventional analysis (Table 7.1 p157). EP from the SIT group did not change in response to training. WEP, although not statistically different post-training in the SIT group, may have been enhanced slightly when compared with END training (see Table 7.2 p158 inferences and Figure 7.5 p160 panel B). These alterations in the all-out parameters are effectively opposite to the conventionally-derived P-D parameter changes.

We originally hypothesised that SIT would result in an increase in both the CP and the W' parameters of the P-D relationship. The conventional analyses reject this hypothesis. However, the P-D parameters from the all-out test provide some support the latter part of this hypothesis; that SIT would result in an increase in the W'. While the 3-min test has been shown to be a valid and reliable test for estimation of the CP and W' parameters (Burnley et al., 2006a; Vanhatalo et al., 2007, 2008a, 2008b; Vanhatalo & Jones, 2009a; Vanhatalo & Jones, 2009b), this is the first time the test has been employed following an all-out cycling training intervention. Due to the 'all-out' aspect of the 3-min test and the similar nature of the SIT employed, there is some evidence to suggest that the post-training 3-min all-out test in the SIT group is detecting a training-specific improvement in the initial 30 s maximal sprint performed (Mohr et al., 2007). However, despite the visual difference in initial 30 s power output of the post-training 3-min all-out test in the SIT group clearly 'causing' the interpreted 'enhancement' in WEP (Figure 7.5 p160, Panel B), there was no statistical difference in work done over the first 30 s of the all-out test pre-and post training. In contrast, due to the increase in the END group's EP, the all-out power profile exhibited a shift 'upward' while maintaining a consistent curvature constant; the relative change in the 'upward' shift in the all-out power curve being the same magnitude as the conventional P-D curve. As a result, the END group exhibited a higher average power over the first 30 s of the all-out test post-training but power output continued to follow a similar, albeit elevated, profile to the pre-training test (Figure 7.5 p160, panel A).

The all-out test data suggest that the SIT group only enhanced (non significantly) their 'anaerobic' capabilities (WEP), having no impact upon the aerobic capability (EP). Based on the consistent benefits of SIT on oxidative markers of muscle metabolism (Burgomaster et al., 2008; Burgomaster et al., 2005; Gibala et al., 2006), it would seem unlikely that the EP parameter of the all-out test is reflecting the CP; and indeed, the two parameters are not in agreement (Table 7.3 p161). Explaining this observation in the all-out test data following SIT is not simple. However, the post-SIT $\dot{V}O_2$ response during the 3-min test exhibits a notable downward trajectory after attaining 3-min $\dot{V}O_{2peak}$ (Figure 7.5 p160, panel D). This is not a typical $\dot{V}O_2$ profile during all-out testing and can only occur should power output fall below CP (Chidnok et al., 2013b; Jones et al., 2010; Skiba et al., 2012). While the power profile of all participants post SIT exhibited no signs of pacing or a non-maximal execution of the test (any that did were repeated on a separate occasion; $n = 1$), over the 6-week training period little-to-no all-out exercise had been completed in excess of 30 s. It is possible that the metabolic milieu that the SIT group had become capable of generating in just 30 s (for example $[K^+]_{ex}$, P_i and ADP accumulation) prevented the muscle from functioning as it could prior to the SIT intervention.

$[K^+]_{ex}$ has a profound depressive effect on force output of muscle action. Similarly to the 'CP concept', below some 'critical $[K^+]_{ex}$ ' muscle force output is maintainable (McKenna, Bangsbo, & Renaud, 2008). Once 'critical $[K^+]_{ex}$ ' is breached, the force capabilities of the acting muscle become limited or compromised (McKenna et al., 2008). Similarly, exercise intensity-induced increases in P_i within the acting musculature will result in a reduction in SR Ca^{2+} release, contributing to the reduced ability of the actin-myosin complex to enter the high-force state (Allen et al., 2008a). In conjunction with the elevation in $[P_i]$, $[ADP]$ increases which, while in isolation may actually aid the force-generating capability of the muscle (Karatzafiri, Franks-Skiba, & Cooke, 2008; Metzger, 1996), substantially reduces the shortening velocity of muscle across a range of $[Ca^{2+}]$ (Metzger, 1996). Considered together, along with the apparent training-specific adaptations expected in response to SIT (Mohr et al., 2007), these rapidly-induced elevations in metabolites within the muscle could help explain the inability of the SIT group to maintain a higher power profile after the initial 30 s of the post-training 3-min test (Figure 7.5 p160, panel B). While this putative

explanation remains speculative, particularly in the face of expected enhancements in muscle buffering capacity (Juel, 2008; Mohr et al., 2007), the possibility of inducing a rapidly achieved critical level of metabolite accumulation within the sprint-trained muscle would be a feasible explanation for what has been observed in the present study. A rapid accumulation of P_i , K^+ and ADP could inhibit muscle action to such an extent that power output cannot be maintained at the CP, thus enabling $\dot{V}O_2$ to fall during the 3-min test duration and invalidating the all-out test parameters obtained. Whereas, when constant-power output within the severe-intensity domain is imposed, the rate at which P_i , K^+ , and ADP accumulate is not maximally challenged and thus muscle force becomes compromised similarly, both pre-and post SIT training; bearing no discernable effect on the CP and W' parameter estimates.

In summary, the present study provides the first clear evidence that despite the highly glycolytic nature of SIT, it is indeed the CP which is positively affected through this mode of training and not the W' of the P-D relationship for severe-intensity exercise. However, the present, non-worked matched data suggest that more conventional endurance training may provide a slightly better or more likely advantage to the CP when the likelihood of worthwhile change is considered. However, a coach or athlete would also need to consider the markedly lower volume of training required to induce a similar increase in CP through SIT. Whether END would prove as effective as SIT in enhancing the CP in a work-matched design remains to be determined but would seem unlikely. The present study also provides further evidence that the 3-min all-out cycling test reliably tracks training-induced changes in CP and W' . However there appears to be a destructive influence on all-out test parameters when exercise training solely focuses on executing the first 30 s of the all-out cycling test which warrants further investigation.

Perspective 4

In contrast to what was originally expected, SIT did not positively affect both CP and W' . Instead, and as the bulk of the existing literature would point toward, SIT resulted in an elevation in the GET, CP and $\dot{V}O_{2\max}$ without affecting the W' . END training resulted in very similar enhancements in GET and CP with no change in W' but did require 15 times the exercise training time commitment when compared with SIT. However, in contrast to the previous chapters within this thesis, the 3-min all-out cycling test did not always provide valid estimates of CP and W' . This was especially so following SIT. While the exact reasons for this remain elusive at present, the test-specific nature of SIT may have played some part in the apparent inability of the SIT group to 'correctly' execute the 3-min test following the 6-week SIT period. It should be noted that in the END group, the 3-min all-out test parameters reliably tracked the changes in the P-D relationship as determined via conventional analysis. The latest observation within this thesis (that the all-out test may not agree with conventional P-D parameters following SIT) is interesting and may warrant further investigation. However, to attempt to elucidate the mechanical, biochemical or physiological reasons for this observation would likely mandate more invasive, or less dynamic exercise models and in doing so would step out with the purposefully practical nature of this thesis. As such, it would be appropriate at this point to review and discuss the contribution of this thesis to current knowledge and the wider area.

Chapter 8 – General Discussion

8.1. Summary of the Main Findings

This body of work aimed to investigate the response of the P-D relationship of all-out exercise when measured under conditions predicted to induce alterations in either the asymptote (CP) or curvature constant (W') of the hyperbolic relationship. In doing so, it was a further aim to gain greater insight into the likely physiological underpinning of the CP and particularly the W' parameters. As such, the main questions addressed were:

- 1) What effect does initiating the 3-min all-out test from an 'elevated metabolic baseline' have on the EP and WEP parameters?
- 2) Can the 3-min all-out test accurately measure remaining W' subsequent to the W' having been reduced by a calculated amount, immediately prior to the 3-min test?
- 3) Is the W' limited by a reduced type I or type II muscle glycogen store when assessed during all-out exercise?
- 4) Is the all-out W' magnitude independent of oxygen availability as its proposed 'anaerobic' nature would suggest?
- 5) Is it possible to enhance the W' with cycle-training and can the 3-min all-out test detect potential changes in the magnitude of the W' ?

Chapter 4; elevated baseline

The 3-min all-out cycling test can be employed from a 'baseline' exercise intensity of moderate-, heavy or severe-intensity and provide reliable EP estimates along with an estimate of WEP remaining that was not different to the calculated WEP remaining (Chapter 4). While the remaining WEP was, on average, 8 % overestimated and 2 % under estimated following an expected 25

and 50 % reduction in WEP respectively, this level of reliability is within the previously reported 8 % variability of WEP (Vanhatalo, 2008).

Chapter 5; glycogen depletion

Unlike W' (Miura et al., 2000), WEP appears to be unaffected by moderate glycogen depletion in predominantly type I or type II muscle fibres (chapter 5). While this may contradict previous research in this specific area (Miura et al., 2000), the performance limiting impact of glycogen manifests itself in 'endurance' tasks (Bergstrom et al., 1967; Jeukendrup, 2004; Maughan & Poole, 1981) but is less likely to affect (even prolonged) sprint tasks (Withers et al., 1991). While the insensitivity of the WEP to detect likely reductions in sustained, severe-intensity muscular endurance capability is a concern for the validity of the WEP in representing the W' , this finding in itself may prove influential in choosing a test for determining the P-D parameters in athletic populations where muscle energy stores will often be compromised (to various extents) depending on preceding training sessions. In this context, the all-out test could prove a useful method to assess current performance capabilities irrespective of preceding training sessions. Consistent with much of the previous literature (Vanhatalo et al., 2007, 2008b; Vanhatalo & Jones, 2009a; Vanhatalo & Jones, 2009b), chapter 4 and the CP concept, the EP parameter is unaffected by reducing finite energy availability within the muscle.

Chapter 6; hypoxia

Moderate hypoxia reduced the magnitude of the EP from the all-out test. In addition, $\dot{V}O_{2\max}$ achieved during the all-out test and P_{ramp} attained during incremental exercise were reduced in hypoxia. Whereas these 'endurance' parameters which rely on oxidative ATP turnover were reduced in hypoxia, the WEP and W' were (based on the group mean) unaffected by hypoxia (although considerable inter-individual variations were observed). This supports the concept that the W' is representative of a volume of work that may be completed independent of O_2 . Chapter 6 also supports the concept that the W'/WEP may represent the relative 'distance' between the CP/EP and P_{ramp} . The strong correlation between the relative change/reduction in CP per unit $\dot{V}O_{2\max}$ ($\% \Delta \text{CP} / \dot{V}O_{2\max}$) and the relative change in W' ($\% \Delta W'$; $r = -0.83$, $P <$

0.001) supports the notion that the W' is equivalent to the 'distance' between the CP and the $\dot{V}O_{2max}$. If the W'/WEP does represent the 'size' of the severe-domain, then a training intervention capable of increasing P_{ramp} without altering CP/EP would result in a larger W'/WEP .

Chapter 7; training

The use of a repeated 30 s sprint interval training (SIT) programme has proved effective at increasing T_{lim} and P_{ramp} in addition to numerous other short-, and longer-duration exercise performances and molecular training stimuli (Bailey et al., 2009b; Burgomaster et al., 2006; Burgomaster et al., 2008; Burgomaster et al., 2005; Gibala et al., 2006; Little et al., 2011; Little et al., 2010a). The reasons (i.e. an increase in CP and/or W') for the improvement in exercise performance observed following this training technique has remained elusive. In chapter 7 it was noticed that the conventional P-D determination method showed no change in W' following 6-weeks of SIT training. The CP on the other hand was increased following SIT. However, the 3-min all-out test appeared to provide an opposing result; no change in the EP yet a small increase in WEP, apparently attributable to work done during the initial 30 s of the all-out test (Figure 7.5 p160, panel B). While this result will be discussed further later on in this discussion, it is noteworthy that, as observed by Mohr et al (2007), the enhancement in 30 s work done during the 3-min all-out test would be a legitimate 'task-specific' adaptation to the training performed. However, this disparity in conventional and all-out P-D parameter estimates casts doubt over the validity of the 3-min all-out test, at least when used to track longitudinal changes in the performance capability of humans performing sprint exercise training.

8.2. Reliability and Validity of the All-Out Test

The reliability of the 3-min all-out test EP and WEP parameters has previously been reported as 3 % and 8 % respectively (Vanhatalo, 2008). While other groups have also presented reliability data from 'all-out' tests (Bergstrom et al., 2014; Johnson et al., 2011), the equipment and exact methods used to conduct the all-out test differ (albeit subtly) from those described originally (Burnley et

al., 2006a; Vanhatalo et al., 2007). In the present thesis, all 3-min all-out tests were conducted in exact accordance with the methodology of the original authors; as such the data presented within (and below) can be added to that of Vanhatalo and colleagues in providing further evidence as to the reliability and validity of the all-out test.

8.2.1. End power (EP)

In chapters 4, 5, 6 and 7 almost all participants performed a familiarisation 3-min all-out cycling test prior to their 'control' or 'baseline' all-out test (on a small number of occasions where participants were very familiar with the all-out test from previous research, a familiarisation trial was not necessary). Furthermore, in chapters 4 and 5, the EP parameter was unchanged under all experimental conditions. As such, these results can be pooled to provide a holistic reliability statistic for the EP parameter of the 3-min all-out test even when employed under differing conditions. There were 124 3-min all-out tests across experimental chapters where EP was not statistically affected by an intervention and/or acceptable familiarisation trials had been performed (i.e. no pacing evident in the power profile). The mean CV for the EP parameter within this thesis was 5 %, or 11 W. The correlation coefficient was $r = 0.96$, $P < 0.001$, $SEE = 19$ W. This 'error' in the EP parameter is inclusive of initiating the 3-min test from anywhere between an 'unloaded' (20 W) and a severe-intensity baseline and under conditions of type I and type II muscle glycogen depletion; therefore, the EP parameter appears very reliable. This is particularly meaningful when one considers the arduous process the participant and experimenter must go through to obtain the CP parameter conventionally, which depending on the mathematical model used for its derivation, will, at best vary by less than 3 % (Bull et al., 2000; Ferguson et al., 2010; Ferguson et al., 2007; Gaesser et al., 1995) but at worst could vary by ~ 18 to 24 % (if comparing CP from two different mathematical models; (Bull et al., 2000; Gaesser et al., 1995)). Therefore, this body of work supports the very good reliability of the 3-min all-out cycling test EP. However, it is noteworthy that in the four participants (18 test-retest 3-min tests) who attained EP values in excess of 300 W, the CV was 7 % which at this magnitude of power (average 316 ± 75 W) results in ~ 22 W of variability (test-retest correlation coefficient, $r = 0.71$, $P = 0.009$, $SEE = 15$

W); in a parameter which defines sustainable and unsustainable exercise, this increase in variability at larger EP values may be a cause for concern for the testing of elite athletes who would, presumably, be capable of higher EP values still. Indeed, this variability may be a contributing factor explaining why, in 'elite' cyclists, the power at EP appears to be unsustainable (McClave et al., 2011). There are also reports that the correctly conducted 3-min all-out test may overestimate CP in 'elite' cyclists (Nicolo & Sacchetti, 2014). However, the present data would suggest the EP underestimates CP by ~ 10 W (Figure 8.1 p176, panel B).

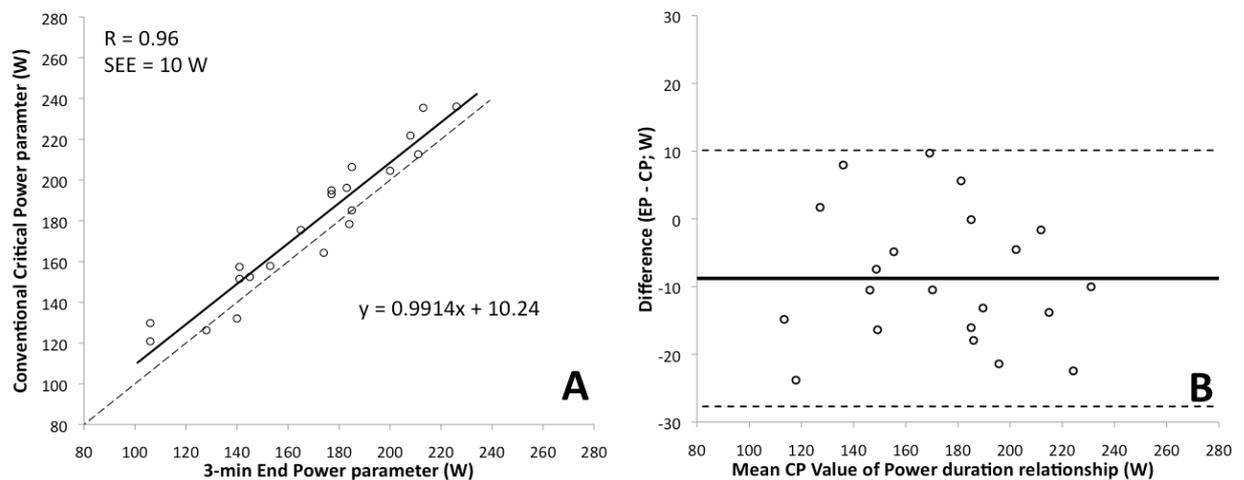


Figure 8.1. Validity and agreement of all-out and conventional CP. Regression plot (panel A) and Bland & Altman plot (panel B) of end power (EP) compared against the criterion measure, critical power (CP).

Validity

While for most (with perhaps the exception of the highly trained), the repeatability of the 3-min test EP is very good, this is of little importance if the parameter does not represent the CP. Previously the 3-min all-out test EP parameter has been shown to correlate very strongly with CP ($r = 0.99$, $SEE = 6 \text{ W}$) with the linear regression of EP against CP essentially falling along the line of identity (when CP was derived from the linear work vs. time model; Fig. 3, p551 Vanhatalo et al. 2007). In the present thesis, the CP and EP parameters were less well matched. Data was pooled from chapter 6 (normoxic conditions) and chapter 7 (both training groups pre-training) and presented in Figure 8.1

p176. The correlation coefficient between CP and EP was $r = 0.96$, $P < 0.001$, and $SEE = 10$ W, with the all-out test typically underestimating CP (mean difference = -9 W; $95\%CI = \pm 19$ W). The slope of the regression was 0.99; a slope of 1.0 would mean the data has a 'perfect' systematic bias and would plot parallel to the line of identity. This is evident in Figure 8.1 p176, panel A and suggests that across the range of EP values obtained within chapters 6 and 7 (106 to 226 W), the all-out test will consistently underestimate CP by ~ 10 W. This is particularly interesting given the current data available suggesting the EP from the all-out test overestimates the heavy-severe-intensity domain boundary (Bergstrom et al., 2013d; McClave et al., 2011; Nicolo & Sacchetti, 2014). While the data of the present thesis does not replicate the near perfect validity of the 3-min all-out test EP parameter presented by Vanhatalo et al. (2007), the larger data pool (21 participants vs. 10) may provide useful additional information in interpreting the likely validity of the all-out test in estimating the CP.

8.2.2. Work above end power (WEP)

In chapter 5, 6 and under certain experimental conditions (those $< CP$) within chapter 4 the WEP was unchanged across experimental conditions. Along with (acceptable) familiarisation trials, these 'repeat' tests were included for a global statistic of reliability in the WEP. The WEP parameter CV was previously reported to be 8 % (Vanhatalo, 2008). Indeed, when 95 all-out tests from across this body of work were compared, the CV was again 8 %. At the magnitude of WEP measured within this body of work (16.3 ± 4.3 kJ), this CV represents just 0.8 kJ of error. The test-retest correlation coefficient was $r = 0.85$, $P < 0.001$, $SEE = 2.3$ kJ. Unlike EP, the WEP showed no indication of becoming more variable with increases in magnitude. While the CV statistic (8 % or 0.8 kJ in the population studied here) appears quite attractive from a practical perspective – that being obtaining a WEP that is 'wrong' by ~ 0.8 kJ is unlikely to cause major inaccuracies in predicting power or time capabilities for a given participant, certainly over longer ($\sim +5$ min) durations of exercise – the SEE (2.3 kJ) is less attractive. Even so, the WEP remains a useful parameter in comparison to alternatives (such as MAOD; discussed in chapter 2, section 2.10. Quantifying Muscular Anaerobic Capabilities), particularly as WEP

reduces predictably at power > EP, conforming to the same mathematics as defined in the conventional CP concept. When WEP is assessed acutely, to define capabilities at a single time point (i.e. no specific ‘training intervention’), the parameter does indeed closely match W' (Vanhatalo et al., 2007). However, this body of work has unearthed a peculiar artifact of the WEP parameter when assessed over time (6 to 9 weeks), in that compared to ‘baseline’, where WEP and W' were closely matched (Chapter 7; W' : 15.7 ± 5.2 ; WEP: 15.6 ± 4.6 kJ) following a sprint training intervention, the WEP diverged from (overestimated) W' (W' : 14.8 ± 5.8 ; WEP: 16.3 ± 4.1 kJ). While this divergence did not reach statistical significance, it trended toward it ($P = 0.059$) and clearly shows a peculiarity in the WEP parameter, which may question its validity in these circumstances.

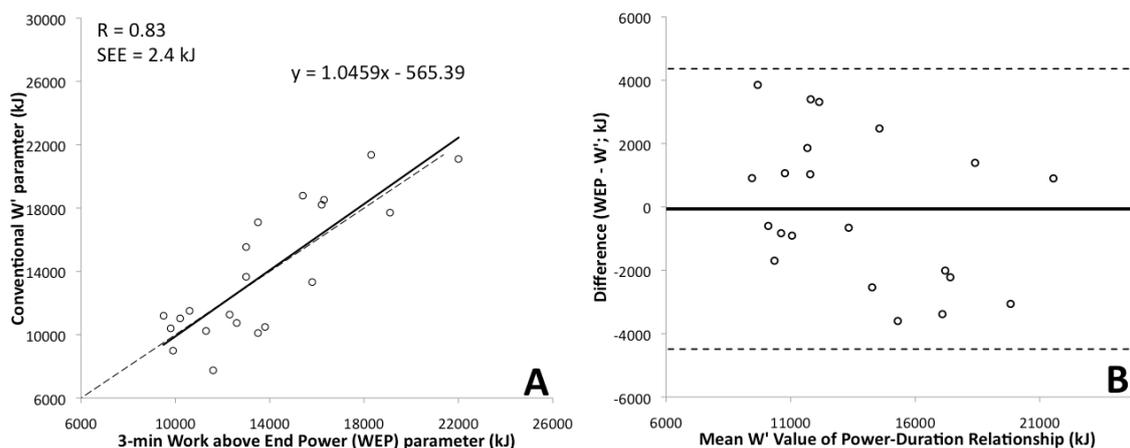


Figure 8.2. Validity and agreement of the all-out and conventional W' . Regression plot (panel A) and Bland & Altman plot (panel B) of work above end power (WEP) compared against the criterion measure, W' .

Validity:

The original publication validating the 3-min all-out test parameters reported a correlation coefficient between W' and WEP of $r = 0.84$, $SEE = 2.76$ kJ, slope of 1.03 and a mean difference ($\pm 95\%$ CI) of $\sim 1 \pm 6$ kJ. This was in a population of 10 males of varying training status. The present thesis has a population

equivalent to 21 repeat tests (equivalent to that of Vanhatalo et al. (2007), i.e. only including data in normoxia and from the pre-training time point) of WEP and W' spanning males and females of varying training status. The validity of the WEP parameter is displayed in Figure 8.2 p178. The correlation coefficient was $r = 0.83$, $P < 0.001$, $SEE = 2.4$ kJ, slope 1.05 and mean difference (± 95 %CI) of -0.01 ± 4.42 kJ. The slope of the regression suggests that typically the WEP is a valid estimate of the W' . Theoretically, based on the slope of the relationship between W' and WEP, at very high magnitudes of W' ($> \sim 25$ kJ), the WEP may underestimate the W' , but this notion would benefit from dedicated examination rather than theoretical extrapolation based on the present data. Encouragingly, the average mean difference between WEP and W' is remarkably small (-0.01 kJ) however, WEP shows considerable individual variation (95 %CI = ± 4.42 kJ). The validity of both the EP and WEP parameters could be brought into question toward the end of chapter 7 as a result of the SIT group exhibiting divergent responses in both EP & CP and WEP & W' . This issue will be discussed further later in this chapter. While the all-out test is not perfectly valid (which would require an $r = 1.0$, $SEE = 0.0$, Slope = 1.0), it can and does provide close approximations in the CP and W' parameters; furthermore, the CP and W' parameters are themselves only as 'accurate' as the model used to derive them (see chapter 2, section 2.2.5. Influence of mathematical model on CP & W').

8.2.3. Predicting severe-intensity exercise tolerance:

Once the CP/EP and W' /WEP are known, the power sustainable for a given duration or the duration sustainable for a given power are calculable. Continuing with the pool of data used above for validity analysis (normoxic data from chapter 6 and pre-training data from chapter 7), and to add further context to the validity statistics, the predicted T_{lim} based on the all-out and conventional CP and W' estimates can be regressed against the actual T_{lim} for given severe-intensity exhaustive bouts (Figure 8.3 p181). Here, the all-out EP and WEP and CP and W' data were used to predict T_{lim} for the shortest, longest and mid-duration constant-power exhaustive bout performed using the equation:

$$T_{lim} = W' / (P - CP) \quad [8.1]$$

Where P is the constant-power and where W' is interchangeable for WEP and CP is interchangeable for EP in order to predict T_{lim} from the all-out test parameters. As can be seen in Figure 8.3 p181, the 3-min all-out test is a poorer predictor of constant-power exercise tolerance compared with the conventional CP and W' parameters (all-out T_{lim} prediction: $r = 0.81$, $P < 0.001$, $SEE = 132$ s; Conventional T_{lim} prediction: $r = 0.99$, $P < 0.001$, $SEE = 40$ s). However, (i) below ~ 400 s (6 min 40 s) predicted vs. actual T_{lim} data-points from EP and WEP are reasonably closely-grouped around the line of identity (Figure 8.3 p181, panel A); (ii) most linear 'endurance' Olympic events last less than ~ 6 min (360 s), thus, perhaps the larger scatter or error in predictive capacity of the all-out EP and WEP parameters may not be a major issue from a practical perspective. Furthermore, it should not be unexpected that when constant-power exercise to the limit of tolerance is used to derive the CP and W' parameters, these parameters are then reasonable at predicting the constant-power exercise tolerance that derived them. Whereas, 3-min all-out test parameters (with the inclusion of PPO from the 3-min test and thus a three-parameter model of power capability; PPO, EP & WEP) would likely be better at predicting shorter-duration (~ 30 to 150 s; extreme-domain) exercise performance capability when compared against CP and W' derived from constant-power exercise trials. The all-out test parameters have recently (Chidnok et al., 2013a) been reported to accurately predict exercise tolerance during constant-power severe-intensity exercise designed to result in exhaustion at 3 min (actual $T_{lim} = 185 \pm 24$ s; $r = 0.99$, $CV = 8 \pm 5$ %). While the exact figures were not presented in the original validation of the 3-min all-out test parameters (Vanhatalo et al., 2007), the predicted T_{lim} from the all-out test tended to underestimate actual T_{lim} by ~ 11 to 28 s over exercise durations spanning ~ 3 to 12 min. The present work also suggests the all-out parameters underestimate actual T_{lim} , however, the magnitude of underestimation is somewhat larger (mean underestimation = -74 ± 131 s) and certainly noticeable compared with the conventional predicted T_{lim} (2 ± 41 s).

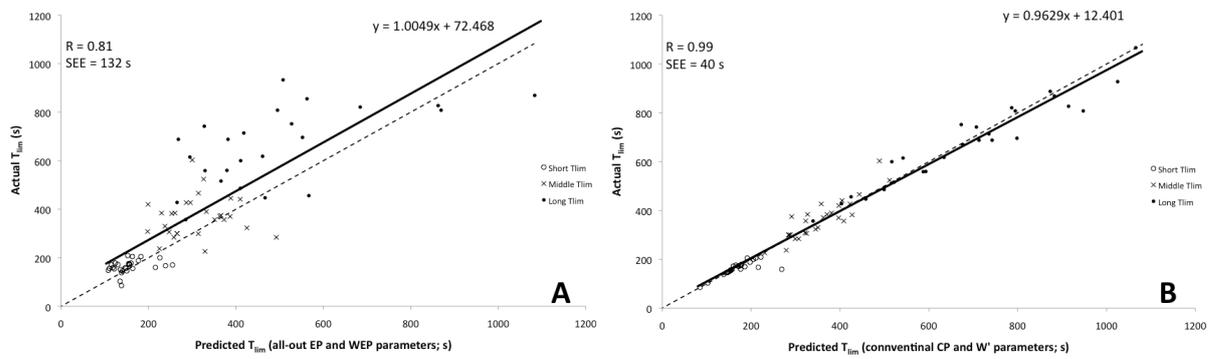


Figure 8.3. T_{lim} predictive capacity of all-out and conventional P-D parameters.

Predicted duration of severe-intensity exercise tolerance (T_{lim}) from all-out (panel A) and conventional (panel B) power-duration parameters compared against actual T_{lim} from exhaustive predicting bouts. All-out & conventional predicted T_{lim} shorter than 0 s and longer than 1200 s were excluded from the analysis. 1200 s was chosen arbitrarily but due to exercise cessation becoming increasingly ‘centrally’ determined, rather than peripherally, which is where the CP concept is derived.

8.2.4. Summary

The 3-min all-out cycling test is a convenient method of characterising the P-D relationship for severe-intensity exercise compared with conventional methods. The EP of the 3-min all-out cycling test is a reasonably reliable parameter (CV = 5 %. SEE = 19 W) even when the all-out test is performed under conditions designed to ‘impair’ exercise performance. In the present body of work, the EP typically underestimated the CP by -9 ± 19 W (mean difference \pm 95 %CI) or \sim 5 %. The WEP of the 3-min all-out test shows much greater variability on a test-retest basis (CV = 8 %, SEE = 2.3 kJ) than does EP. Even so, the test-retest correlation coefficient ($r = 0.84$) remained high and the validity of the WEP appears to be very good (Figure 8.2 p178). However, in the heteroscedastic group of humans studied here, while the mean WEP for the group closely matched that of the mean W' (as observed in chapter 6), this may ‘mask’ the variability in this parameter on an individual basis. When taken together, the variability in EP and WEP can result in poor T_{lim} predicting capabilities of these two parameters over a wide range of exercise durations/severe-intensity power outputs. However, this occurrence would be under ‘worse case’ conditions; practically, the 3-min all-out test provides EP and WEP parameters which, over durations of performance spanning \sim 30 s to 6 min offer good predictive capabilities.

8.3. Response of EP to Specific Manipulation

In the section above, data were pooled from across this thesis whenever EP was unaffected by an intervention. In ~ 50 % of this thesis the EP was purposefully manipulated in an attempt to characterise the concomitant effect on WEP. The majority of the existing literature examining the responses of the CP and W' to interventions (e.g. hypoxia, hyperoxia, exercise training, blood donation) have identified that the CP is a relatively plastic parameter, changing with alterations in O₂ availability (Dekerle et al., 2012; Moritani et al., 1981; Valli et al., 2011; Vanhatalo et al., 2010a), and as a result of metabolic adaptations induced by exercise training (Gaesser & Wilson, 1988; Jenkins & Quigley, 1992; Poole et al., 1990; Vanhatalo et al., 2008a). The CP appears to be, to some extent at least, independent of the $\dot{V}O_{2max}$ (Gaesser & Wilson, 1988), being able to increase/decrease as a fraction of $\dot{V}O_{2max}$. On the other hand, when the $\dot{V}O_{2max}$ is increased, the CP will typically increase similarly, thus remaining at a similar fraction of the $\dot{V}O_{2max}$ (Poole et al., 1990; Vanhatalo et al., 2008a). In chapter 6, the ΔP_{ramp} and ΔEP as a result of hypoxia had a moderate relationship ($r = 0.48$, $SEE = 12$ W). This relationship may help account for some of the 'shift' in the fraction of P_{ramp} at which EP occurred (Normoxia: 70 ± 9 ; hypoxia 64 ± 8 % P_{ramp}) under the hypoxic condition.

The EP parameter of the all-out test does show some variability (Figure 8.1 p176). At best the EP can provide estimates of CP that are as reliable as any conventional CP estimate (~ 3 %) and not different in magnitude to the actual CP (Vanhatalo et al., 2007). When used under the conditions within this thesis, the EP parameter exhibited slightly larger variability both in terms of test-retest reliability and validity to the CP parameter. However, where the EP was invalid (chapter 7), it appears to be systematically invalid and remained so over time in the population studied (~ 20 W underestimation of CP), thus as a means of measuring change in response to an intervention, it provides useful data. As the 3-min test is inherently a practical test (compared to the cumbersome conventional method of deriving CP and W'), reliability is arguably more important than validity. Furthermore, given the 'critical' nature of CP, being the

'threshold' between sustainable and unsustainable exercise intensities, and the other methods of approximating a similar proxy (lactate turn point, respiratory compensation point, MLSS), the EP of the 3-min all-out test, even under unfavorable conditions (i.e. under-/over-estimating CP by ~ 10 W), probably still offers the best solution to the problem of identifying the 'critical' intensity of exercise.

8.4. WEP Responses to Specific Manipulation

While the CP concept does not (with the exception of the exponential models where only CP is determined) allow for the study of either the CP or W' in isolation, the over-riding theme of this thesis has been to observe changes in and the behavior of the WEP/ W' in response to various environments or interventions in an attempt to better understand the likely physiological underpinnings of this key parameter. Based on the work of Vanhatalo and colleagues (2006 to 2010), the 3-min test appears to be a reliable and valid method of determining the P-D parameters for severe-intensity exercise. In chapter 4, the 3-min all-out test was used exclusively to initially characterise the P-D relationship before using the EP and WEP to predict an exercise intensity that would be tolerable for 8 min. Completing 2 and 4 minutes of exercise at this power should result in a 25 and 50 % reduction in WEP respectively. Given the 'noise' in the WEP measure, both the ability to predict WEP reduction and the ability of the all-out test to detect the reduced WEP was unearthed. Furthermore, and as the CP concept and assumptions would suggest, when exercise was performed at intensities below the EP, prior to the all-out test, WEP was unaffected. This chapter added further support that the 3-min all-out test provides a reliable measure of the P-D relationship and that the test can detect subtle, but meaningful alterations in the instantaneously available WEP. Support was also provided for WEP/ W' being utilised at work rates above CP in a predictable manner, dependant upon the magnitude of the exercise intensity above CP (Ferguson et al., 2010; Ferguson et al., 2007; Fukuba et al., 2003). Knowing that the all-out test reliably determined the parameters of the P-D relationship and sensitively detected the expected changes in the WEP parameter, it appeared appropriate to attempt to alter the magnitude of the

WEP via other means, thereby testing the sensitivity of the all-out test under different circumstances.

We sought to reduce the muscle glycogen pool within the exercising musculature and observe the response of the WEP. Reducing muscle glycogen content has previously been shown to reduce the W' of the P-D relationship (Miura et al., 2000) when determined via three, constant-power exhaustive exercise bouts. By selectively depleting muscle glycogen in either predominantly type I or type II muscle fibres, we expected to observe reductions in the EP and WEP respectively (Chapter 5). For a number of reasons (see section 8.5 – limitations), not least that all-out exercise appears to consume $\sim 10 \text{ mmol}\cdot\text{kg}^{-1}\cdot\text{ww}^{-1}$ muscle glycogen for every additional 30 s of all-out exercise performed in one bout (i.e. 30 s consumes ~ 20 , 60 s consumes ~ 30 and 90 s consumes $\sim 40 \text{ mmol}\cdot\text{kg}^{-1}\cdot\text{ww}^{-1}$ muscle glycogen; (Withers et al., 1991)) the extent of glycogen depletion induced may have been insufficient for WEP to be notably reduced. As all-out exercise continues past ~ 90 s, participants are likely to be at $\dot{V}O_{2\text{max}}$ (Burnley et al., 2006a; Chidnok et al., 2013a; Vanhatalo et al., 2007) and importantly, power output will have fallen precipitously to somewhere below P_{ramp} but above GET. Thus aerobic ATP turnover is likely to outweigh that of anaerobic glycolysis (glycogenolysis; (Romijn et al., 1993)). Taken together, an expected $\sim 50\%$ depletion of glycogen in type II muscle fibres would potentially be insufficient to cause a reduction in the WEP/ W' determined via all-out exercise (i.e. if resting levels approach $\sim 120 \text{ mmol}\cdot\text{kg}^{-1}\cdot\text{ww}^{-1}$ (Withers et al., 1991) then a $\sim 50\%$ reduction would result in $\sim 60 \text{ mmol}\cdot\text{kg}^{-1}\cdot\text{ww}^{-1}$ which would likely be sufficient to support a single all-out exercise bout of 3-min duration). Whereas, when square-wave high-intensity exercise is performed in a state of high or low muscle glycogen content, exercise is enhanced and compromised respectively (Maughan & Poole, 1981). It is not surprising then that determining the CP and W' conventionally would result in compromised T_{lim} when high-intensity, constant-power exercise bouts are performed in a glycogen depleted state. Chapter 5 highlighted the requirement to conduct all-out tests alongside the conventional P-D relationship methodology (as had been the case in existing literature (Vanhatalo et al., 2007, 2008a)) to ensure WEP was providing a valid estimate of the W' .

Whereas attempting to conduct all-out and conventional CP & W' determination in chapter 5 would have lead to an intolerably arduous experimental protocol (~ 22 to 32 visits), by changing only 1 variable (F_{iO_2} : chapter 6), running both all-out and conventional methods alongside each other was much more practical. Based on existing evidence available at the time of completion of chapter 6, moderate hypoxia was reported to reduce $\dot{V}O_{2max}$ and CP yet leave the W' unaffected (Moritani et al., 1981). This would suggest that the CP is an aerobically-underpinned parameter, whereas the W' is predominantly 'anaerobic' in its nature (Dekerle et al., 2012; Fukuba et al., 2003; Hill, 1993; Moritani et al., 1981; Poole et al., 1988). With chapter 5 having attempted to test the hypothesis that the WEP/W' represents a high-energy store within the muscle, chapter 6 was focused on the more recent hypothesis that the W' may represent the relative 'size' of the severe-intensity domain (Burnley & Jones, 2007; Vanhatalo et al., 2010a). Moderate hypoxia was used to test this proposal due to hypoxia causing an expected reduction in both the $\dot{V}O_{2max}$ and the CP/EP (Dekerle et al., 2012). If the reduction in both CP and $\dot{V}O_{2max}$ was similar then the relative distance between the two parameters would be unaffected and thus the 'size' of the severe domain would remain constant, theoretically leaving the W' unchanged (Burnley & Jones, 2007). Indeed a significant correlation was observed between the relative change in $CP/\dot{V}O_{2max}$ and the relative change in W' ($r = 0.83$, $P < 0.001$; Chapter 6, Figure 6.2 p139). That is, CP reduced by ~ 25 % in hypoxia, $\dot{V}O_{2max}$ reduced by ~ 14 %. Therefore, the 'distance' between CP and $\dot{V}O_{2max}$ increased, and this was associated with a ~ 8 % increase in the W', supporting the notion proposed by Burnley & Jones (2007). Vanhatalo et al. (2010) and later Murgatroyd et al. (2011) linked the tolerance to severe-intensity exercise to reaching nadirs in pH, PCr, P_i and $\dot{V}O_2$ slow component amplitude/ $\dot{V}O_{2max}$ respectively, with the magnitude of the W'. While this doesn't offer an explanation as to what physiologically underpins the W', it does offer insight into the likely mechanisms of fatigue which simultaneously both limit severe-intensity exercise tolerance and thus determine the mechanical work which may be performed at intensities > CP.

The W' has been linked to the $\dot{V}O_2$ slow component amplitude (Murgatroyd et al., 2011); that being a larger amplitude of the $\dot{V}O_2$ slow component is likely to

result in a larger W' . However, it has also been demonstrated that the W' increases when exhaustive predicting bouts are preceded by heavy-intensity priming bouts (Burnley et al., 2011). This is interesting because priming exercise is typically associated with a larger primary amplitude of the $\dot{V}O_2$ response and a concomitantly reduced $\dot{V}O_2$ slow component amplitude (Bailey et al., 2009a; Burnley et al., 2002; Poole & Jones, 2012). It is logical to assume W' would be 'maximized' under the priming condition due to 'turning on' aerobic machinery within the muscle more quickly and thus deriving a slightly higher proportion of ATP from aerobic pathways. Such an effect may serve to 'spare' some of the W' ostensibly used in the transition to severe-intensity constant-power exercise; enabling the 'spared' W' to be utilised to extend T_{lim} at the supra CP power output. While $\dot{V}O_2$ kinetic responses offer an exceptional non-invasive insight into what is occurring across the muscle during dynamic, whole-body exercise (Barstow, Lamarra, & Whipp, 1990; Grassi et al., 1996; Koga et al., 2005; Rossiter et al., 1999; Whipp et al., 1982b), it is a proxy for muscle $\dot{V}O_2$. The more frequent use of ^{31}P -MRS to interrogate the real-time changes in intramuscular metabolites has enabled greater mechanistic understanding of the likely causes of muscle fatigue, which has largely supported modern fatigue theory (Allen et al., 2008b; Fitts, 1994; Westerblad & Allen, 1993) which was based on acute time-point biopsy work, often in animal models. More recent investigations have elegantly portrayed the metabolic consequences of $>$ CP exercise; causing exorable rises in P_i , and reduction in PCr and pH (Burnley, Vanhatalo, Fulford, & Jones, 2010; Chidnok et al., 2013b; Jones et al., 2008; Vanhatalo et al., 2010a). These exorable consequences appear to nadir at a consistent level irrespective of T_{lim} (Vanhatalo et al., 2010a), support perhaps for the W' 'accumulation' hypothesis. While the absolute nadir value of these (and presumably other) metabolites appear to consistently coincide with voluntary exhaustion, the rate at which these nadirs are attained has yet to receive much attention and furthermore, is potentially unlikely to be maximally challenged through severe-intensity constant-power exercise.

While the current work has not examined the molecular perturbations occurring within the muscle, it has provided some evidence that the rate at which work may be performed could be elevated following a period of training specific to this ability/requirement (chapter 7). SIT appears to have enabled participants to

accumulate a greater amount of work within a 30 s period (the specific duration 'trained'). However, with this higher PPO and subsequent work done over 30 s (post training) yet the identical EP, the curvature of the all-out power profile (presumably) must have become 'steeper' or reduced precipitously at a greater 'rate' when compared with pre-training. However, this suggestion may be somewhat premature or speculative, particularly before the execution of this post-training 3-min all-out test is considered.

In chapter 7 the striking abnormality observed in the all-out P-D parameters following 6 weeks of SIT did not concur with the changes in P-D parameters obtained from conventional methods. While pre-training the EP and WEP approximated CP and W' reasonably closely, post-training, the direction of change in each the CP and EP and the W' and WEP parameters opposed each other. That is, following SIT, the CP and W' increased and did not change respectively while the EP and WEP did not change and increased respectively (EP was significantly different to CP at all time points (underestimating CP) albeit WEP was not statistically different from W' (chapter 7, Table 7.2 p158). Under these circumstances doubt could be cast over the validity of the 3-min test in estimating the CP and W' . However, this need not be the case. As discussed in chapter 7, the post-training all-out test in the SIT group appears to not meet the criteria for a valid test execution; the downward trend in $\dot{V}O_2$ away from $\dot{V}O_{2max}$ over the final half of the post-training 3-min test (chapter 7, Figure 7.5 p160) is indicative of power output falling below the CP (Billat et al., 2013; Chidnok et al., 2013b). It is worth stating that a systematic 'leak' in the seal between participant and mouthpiece was not the cause of this decrease in $\dot{V}O_2$ during the post-training, all-out test in the SIT group, which would be an (albeit a peculiar) explanation for this observation. Rather, the explanation(s) for the apparent inability to perform the 3-min all-out test correctly following a period of specific sprint cycle training may be due to the specificity of the training completed.

Numerous examples within the literature show that short-duration, maximal or all-out/sprint performance is enhanced following all-out type training (Bangsbo et al., 2009; Barnett et al., 2004; MacDougall et al., 1998; Mohr et al., 2007; Nevill, Boobis, Brooks, & Williams, 1989; Parra et al., 2000). While we did not

assess 'sprint performance' per se outside of the training sessions performed, the SIT group appear to have improved their performance (power output) over the initial ~ 30 s of the post-training all-out test (chapter 7, Figure 7.5 p160, panel B). However, after the initial ~ 30 s, the power profiles of the pre- and post-training all-out tests were essentially identical. Given the measured increase in CP following the training period in the SIT group and the identical power profile pre- and post-training from ~ 30 s onward in the all-out test, it is entirely feasible that the power output during the all-out test (post-training) did indeed drop below CP, enabling $\dot{V}O_2$ to fall. However, this response was observed across the SIT group, suggesting some form of systematic inhibition of the ability to correctly perform the test, despite apparently providing a maximal effort throughout. This observation is difficult to explain but potentially could be due to the rate at which fatigue-implicated metabolites accumulate within the muscle (Allen et al., 2008b; Debold, 2012a).

Constant-power and all-out exercise can be considered 'polarized' in the time-course of physiological perturbation observed. Constant-power severe-intensity exercise will result in a progressive but continued accumulation of metabolites (Burnley et al., 2010; Jones et al., 2008; Vanhatalo et al., 2010a). All-out exercise will presumably cause a rapid and early accumulation of these metabolites, which will thus impair muscle force production and exercise performance (Allen et al., 2008a, 2008b; Allen & Trajanovska, 2012; Debold, 2012b; Westerblad & Allen, 2002). Assuming a training-specific adaptation was gained from SIT (which appears to be supported by the initial 30 s of the post-training all-out test; Figure 7.5 p160, panel B), the SIT group will have likely accumulated a greater magnitude of metabolites, detrimental to muscle force production, within the initial 30 s of the all-out test. This would be a positive adaptation for short-duration muscular performance (i.e. the ability to 'accumulate' the most amount of work in a 30 s period, irrespective of the metabolic consequences) but one that may not translate to an improved performance of a longer 'sprint'. The majority of the SIT groups' training for the prior 6-week period had ceased at 30 s. When, in the all-out test, the muscles were required to continue exercising for an additional 150 s, post-training, in the face of the likely 30 s-specific adaptations gained, the 'normal' fatigue characteristics of the power profile could have altered, resulting in the inability

for the SIT group participants to sustain a sufficiently high muscle force output, despite a (presumed) maximal drive to the muscle to do so.

8.5. Limitations

Within the current body of work there were a number of limitations that should be highlighted. These will be detailed here.

8.5.1. Experimental limitations

Chapters 4 and 5 exclusively employed the all-out test to characterise the P-D relationship for severe-intensity exercise. While this was a deliberate methodological decision, initially (chapter 4) as a 'proof of concept' design to define the ability of the all-out test to (i) provide reliable EP and WEP estimates when initiated from an elevated power output and, (ii) detect predicted reductions in the WEP induced by prior severe-intensity exercise. Following the apparent ability of the test to provide suitable and expected results to both (i) and (ii), along with the previously published example of the 3-min all-out test providing valid estimates of the CP and W' (Vanhatalo et al., 2007), it was deemed appropriate to continue to employ the all-out test exclusively in the subsequent experiment (chapter 5). Furthermore, and as mentioned previously, to employ the conventional determination of CP and W' alongside the all-out test in chapter 5 would have resulted in an experimental protocol requiring ~ 22 to 32 visits, with at least 6 of these visits requiring the completion of 3 hours of moderate-intensity cycling. It is acknowledged that the inclusion of these conventional visits would have greatly aided both our understanding of the validity of the all-out test parameters under the muscle glycogen depleted conditions studied and potentially provided some firm evidence of the all-out test and the conventionally determined parameters differing through virtue of the polarized approaches to ascertaining the parameter estimates. Furthermore, chapter 5 would have greatly benefited from some method of quantifying glycogen content in specific fibre pools. While conventionally this has been assessed invasively through muscle biopsy (Bergstrom et al., 1967; Carter et al., 2004; Heigenhauser, Sutton, & Jones, 1983; Khowaja, Choi, Seaquist, &

Oz, 2014; Stephenson et al., 2013; Withers et al., 1991), newer, non-invasive techniques, such as ^{13}C -MRS, are also possible (Khowaja et al., 2014; Stephenson et al., 2013). However, neither technique was employed due to a lack of facility and skill-set to do so and as such, any extent of glycogen depletion is assumed based on previous literature employing an almost identical glycogen depletion protocol (where biopsy-derived quantification of glycogen depletion was confirmed; (Carter et al., 2004)). While the results of chapter 5 do not agree with those of Miura et al. (2000), it is pertinent to point out that at present, no experimental paper exists where the P-D relationship has been characterised while muscle glycogen has been compromised to any objectively measured extent; that is both Miura et al. (2000) and the present thesis have assumed a degree of muscle glycogen depletion based on the work of previous experimental papers (Carter et al., 2004; Heigenhauser et al., 1983). The glycogen depletion protocols employed in the present thesis were non-exhaustive, contrasting exercise bouts; one low intensity sustained duration and one high-intensity but intermittent. Miura et al. (2000) employed a depletion protocol comprising sustained, (likely) heavy-intensity cycling, followed by intermittent high-intensity exercise, which was continued until exhaustion. While both depletion protocols (that of the present thesis and of Miura et al (2000)) have been reported to result in ~ 50 % muscle glycogen depletion, it is apparent that the Miura et al (2000) protocol was very demanding for participants. Furthermore, participants were clearly conducting exhaustive exercise within the immediate ~ 15 hours prior to exhaustive P-D predicting bouts. While as little as 30 min has been permitted between repeated P-D predicting trials (Housh, Housh, & Bauge, 1990), it is typical for predicting trials to be conducted on separate days, having not performed strenuous exercise on the day prior, and this was indeed the stipulation in the non-depleted condition of the Miura et al. (2000) paper. As such, the influence of exhaustive exercise in the hours prior to P-D predicting trials should not be overlooked, particularly because this was not conducted in the non-depletion condition. Furthermore, the non-significant ~ 6 W (3 %) reduction in CP under the depleted condition and the ~ 2.5 kJ (19 %) reduction in W' may (in accordance to the original hypothesis in chapter 5) suggest that glycogen depletion, or exhaustive exercise the evening before P-D predicting trials, reduce both W' and CP. The direct influence of objectively

quantified muscle glycogen depletion on the P-D parameters from both conventional and all-out methods remains an area for clarification.

Chapter 7 provided a quite unexpected result in the SIT group following 6-weeks of sprint training in that the all-out test suggested no change in the EP parameter but a potential increase in the WEP parameter, while the conventional methods suggested an increase in CP with no change (slight decrease) in the W' . As discussed previously, the SIT group appeared to be unable to correctly perform the post-training all-out test, with $\dot{V}O_2$ not being held at $\dot{V}O_{2max}$ for the duration of the test. While this is an interesting discovery, without subsequent follow-up all-out tests, we have little to help explain why this may have been observed. Upon discovery of this phenomenon, it would have added strength to our understanding to repeat these post-training 3-min tests at weekly intervals (with the SIT group) to determine whether this is a genuine, and lasting effect of SIT on 3-min test performance, or if it was a curious coincidence that the SIT group each exhibited a similar inability to 'correctly' perform the test. To this end, an additional limitation of this body of work would be the direct insight (or lack thereof) into the mechanistic underpinning of the W' .

This thesis attempted to use the 3-min all-out test in novel circumstances to help provide insight into the likely physiological determinants of the W' /WEP. While this body of work has provided some supporting evidence that the all-out test parameters represent the CP and W' it has also provided some interesting and possibly conflicting evidence (chapter 7) for this assertion. The current body of work has not provided any direct evidence as to the physiological constituents, mechanisms or underpinnings of the W' . However, alongside this work, a number of authors have tackled some of these areas (Chidnok et al., 2013b; Ferguson et al., 2010; Murgatroyd et al., 2011; Skiba et al., 2012; Vanhatalo et al., 2010a). The information now available in the more recent literature enables a far greater depth of interpretation of the likely mechanistic explanation(s) of the observations within this thesis, but nonetheless, the examination of intra-muscular changes alongside any one of the chapters within this thesis would provide far greater mechanistic insight. Doing so however, would inevitably draw the experiments further from whole body dynamic

exercise and thus make the investigations less 'practical'; detracting perhaps from the very essence of the all-out test.

8.6. Contribution to the Area

The original 3-min all-out cycling test first presented by Burnley et al. (2006) provided the first evidence that the heavy-severe-intensity boundary could be determined via a single, all-out exercise test. The subsequent series of publications by Vanhatalo et al. (2007, 2008a, 2008b, 2009a, 2009b) provided evidence of the tests validity, reliability and utility in assessing the acute and chronic effects of interventions on the P-D relationship. Since then, the all-out test (or tests of a similar nature, but notably differing methodology) has become much more widespread (Bergstrom et al., 2012; Bergstrom et al., 2013b; Bergstrom et al., 2013c, 2013d, 2013e, 2014; Black, Durant, Jones, & Vanhatalo, 2014; Chidnok et al., 2013a; Constantini et al., 2014; Francis et al., 2010; Johnson et al., 2011; McClave et al., 2011; Nicolo & Sacchetti, 2014) and to some extent is likely responsible for the increased interest in the area of CP. As such, the work within this thesis provides important evidence of how the all-out test will respond and how it should be adjusted for successful CP and W' estimates under a number of 'new' conditions.

This thesis provides evidence that the 3-min all-out test, when conducted according to the original methods of Burnley et al. (2006) and Vanhatalo et al. (2007) provides valid estimates of CP and W' (chapter 6; chapter 8 figures 8.1 & 8.2). The test parameters are predictably affected when the test is initiated from elevated power outputs (chapter 4). The resistance setting within the ergometer is vital for successful determination of valid WEP parameters, and in conditions where the EP is expected to be affected (hypoxia, blood donation, hyperoxia, EPO administration or exercise training), the test resistance should be set according to the P_{ramp} and GET in the environment/condition of interest, otherwise, as observed by Vanhatalo et al. (2008b), the WEP is likely to be over- or under-estimated (depending on the direction of change in EP; elevation in EP, WEP underestimated; reductions in EP, WEP overestimated). There is additional supporting evidence within chapter 6 that the W' parameter may

partly represent or be determined by the magnitude of the severe-domain or relative distance between CP and $\dot{V}O_{2max}$. Additionally, when exercise training is conducted which is non-specific to a given portion of the all-out test (i.e. within the heavy-domain), the 3-min test can track changes in CP and W' . However, chapter 7 highlights that caution should be exercised when using the 3-min test to track changes in the P-D parameters following/during a period of short-duration sprint training.

8.7. Practical Applications

The evidence within the current thesis may have a number of practical implications for the use of the 3-min all-out test. Perhaps most notably, and as mentioned in chapter 5, the 3-min test provides reliable EP and WEP parameters irrespective of whether (i) 24 hours of rest, (ii) prolonged low intensity exercise, or, (iii) repeated high-intensity interval exercise are employed on the evening preceding the all-out test. This would suggest that in addition to 3-min all-out test being a rapid method of determining the P-D relationship, it could be used at any point in an athlete's training programme yet be unaffected by preceding training sessions; therefore providing reliable information about physiological adaptation. In light of the observations with the all-out test post SIT training (chapter 7), whereby the test appeared to be affected by the test-specific nature of the SIT, it is prudent to point out that (typically endurance) athletes are unlikely to follow a training programme comprising just sprint training. Therefore (as observed elsewhere; (Vanhatalo et al., 2008a)) under typically varied training, the 3-min test is likely to track changes in the P-D relationship.

8.8. Future Directions

The obvious area for further exploration following the work contained within is to explain why the 3-min test did not track changes in CP and W' following SIT. As alluded to earlier, it is likely that the rate of accumulation of fatigue-implicated metabolites within the muscle may have been higher following training. Through the use of ^{31}P -MRS pre and post training during an all-out critical torque test

(Burnley et al., 2010), the kinetics of P_i accumulation, PCr and pH decline and potentially Ca^{2+} and K^+ cycling could be studied. This, in combination with quantification of 'anaerobic' enzyme concentration and activities, would shed light on how training-specific alterations in muscle metabolism may differ depending on the type of training conducted.

Additionally, in light of the 3-min test spanning both extreme- and severe-intensity exercise intensities, it would be interesting to incorporate a mathematical characterization of the curvature decline in power output from PPO through to EP, most likely using some form of exponent similar to that of Weyand et al. (2006). The additional benefit of the 3-min all-out test is that cadence is not held constant, unlike the isokinetic work of others (Brickley et al., 2007; Bundle & Weyand, 2012; Dekerle, Barstow, Regan, & Carter, 2013; Weyand et al., 2006) which has proved poor at obtaining estimates of W' or CP. Furthermore, moving through a cadence range during all-out exercise simulates 'real world' cycling performance far greater than artificially clamping cadence at 'optimal' or any other point either side thereof. However, the work of Bundle & Weyand (2012) suggests that all humans exhibit essentially the same exponential fatigue profile when power/torque is normalized between PPO and maximal aerobic power. While this is interesting and an observation that Weyand believes is robust, it is only true of isokinetic performances, lacking 'real world' applicability. Successfully integrating a mathematical description of the power profile within the 3-min all-out test would enable a third means of comparing differences in performance capabilities in addition to EP and WEP.

The WEP parameter of the all-out test is known to show $\sim 8\%$ variability, much like the W' parameter (Ferguson et al., 2010; Vanhatalo, 2008). While the CP model (all-out or conventional) likely provides the most practical and reliable means of quantifying the volume of anaerobic work a human can perform, the validity and reliability of the EP under many different conditions must not be overlooked. Certainly from a practical perspective, where athletes are more and more opting to train and race with power measuring devices on their personal bikes, the determination of the EP alone should provide enough information to then determine the magnitude of the W'/WEP through the analysis of training/race data. Additionally, the W' could be iteratively defined through a

specific interval session designed around the EP parameter only. These means of determining the W' or WEP, while not yet scientifically tested, offer a very practical means of subtly incorporating the study of the P-D relationship into the training programmes of athletes without undue stress or additional 'laboratory' sessions. The development of simple models of determining the magnitude of the W' from training data would further help embed the CP concept throughout the world of applied physiology within sport.

Finally, given the potential utility of the all-out test parameters for athletes, it seems reasonable to suggest that the test procedures proposed by Burnley et al. (2006) could in fact be replicated either out on specific public roads or on modern-day sophisticated stationary turbo trainers. That being, for a given mass of a rider and bike combination, a given grade of road (or simulated grade) and a specified gear ratio, the power output at a 'preferred' cadence could be calculated giving rise to extremely similar resistance settings as used in the electromagnetically-braked lode ergometer used in the original 3-min test. The advantage of this set up for the athlete with their own power meter is that there is likely to be no discrepancy between the power output 'measured' by the ergometer and that of their own bike, therefore removing an additional source of variability/error.

8.8. Conclusion

The P-D relationship for severe-intensity exercise can be validly characterised using all-out exercise, providing the equipment and methodology employed is carefully prepared according to the work of the original authors (Burnley et al., 2006a). The EP and WEP parameters from the 3-min all-out test can be used to validly determine severe-intensity power outputs which will result in exhaustion within a predictable duration and furthermore, the 3-min all-out test is able to detect the 'amount' of WEP remaining at any given time when the all-out test is initiated from within the severe-intensity domain. This is of particular utility if attempting to determine the 'cost' to the W' parameter of prior high-intensity exercise performance. For example, accelerating a bike from stationary to a fast speed requires more energy than does accelerating the bike by the same

magnitude but from a rolling (rather than standing) start. However, despite this knowledge, the scientific or coaching community appears not to have a grasp of quantifying this energy cost; the 3-min all-out test could provide the answer.

The EP and WEP parameters of the 3-min all-out test are unaffected by moderate levels of muscle glycogen depletion. While this could be viewed as insensitivity of the all-out test, it is more likely that muscle glycogen does not become limiting to all-out sprint performance of just 3 min duration. While reduced/elevated muscle glycogen levels have the potential to compromise/enhance severe-intensity exercise tolerance respectively (Maughan & Poole, 1981), it is not yet definitively clear whether CP or W' are affected by reduced muscle glycogen per se, or rather the effects of the exercise required to induce muscle glycogen degradation. Certainly carbohydrate and muscle glycogen play a number of additional roles within the body relating to adaptive metabolic signaling (Baar, 2014), SR Ca²⁺ handling (Gejl et al., 2014) and potentially central fatigue (Meeusen, 2014). However, the contribution of muscle glycogen per se to the magnitude of the W' has yet to be conclusively determined, but is unlikely to be possible using the all-out cycling test.

The 3-min all-out cycling test can be conducted under hypoxic conditions and provide valid estimates of CP and W' providing the ergometer resistance is adjusted relative to the performance of ramp incremental exercise in hypoxia. As expected, the diminished availability of O₂ at the muscle caused a reduction in CP and $\dot{V}O_{2max}$. The relatively similar reduction in these two aerobically-determined parameters resulted in an unchanged W' in hypoxia. This supports the notion that the W' is inherently anaerobic in its composition, but also supports the premise that the W' may in fact represent the relative 'size' of the severe-intensity domain; i.e. the distance between CP and $\dot{V}O_{2max}$ and thus the area within which an exorable $\dot{V}O_2$ slow component may emerge. Interventions capable of decreasing CP yet increasing $\dot{V}O_{2max}$ should therefore result in an increase in the W', or simply increasing $\dot{V}O_{2max}$ without affecting the CP should also result in an increased W' and translate to a short-duration performance enhancement.

The recently reported increases in severe-intensity exercise tolerance following a short period of SIT (Bailey et al., 2009b) are likely due to an increase in CP with the W' being unaffected. Certainly this observation would concur with the numerous publications demonstrating the potent stimulus SIT provides for mitochondrial biogenesis (Gibala, 2009; Jacobs et al., 2013; Little et al., 2011; Little et al., 2010a; Little, Safdar, Wilkin, Tarnopolsky, & Gibala, 2010b). SIT also provides a time efficient means of inducing similar changes in CP compared with sustained, strenuous, heavy-intensity exercise. However, while the 3-min all-out test reliably tracked changes in CP and W' when endurance training was conducted, it appeared to be affected by the 'test-specific' training modality in the SIT group. This led to the all-out test not reliably tracking changes in the P-D relationship based on the conventional determination method. Furthermore, additional evidence is provided to support the notion that the W' is not 'trainable' through the use of conventional dynamic exercise (cycling/running/swimming etc.).

In summary, the all-out test can be used in a number of circumstances and return valid and reliable CP and W' estimates. Certainly in a research context, investigating the effects of an acute intervention on the P-D relationship, the all-out test is a viable and practical alternative to the conventional method. However, at present, based on the results presented here, the use of the all-out test as a means to monitor longitudinal adaptations to exercise training should continue to be employed in combination with the conventional methodology.

Bibliography

- Abbiss, C. R., & Laursen, P. B. (2005). Models to explain fatigue during prolonged endurance cycling. *Sports Med*, 35(10), 865-898. doi: 35104 [pii]
- Ahlquist, L. E., Bassett, D. R., Jr., Sufit, R., Nagle, F. J., & Thomas, D. P. (1992). The effect of pedaling frequency on glycogen depletion rates in type I and type II quadriceps muscle fibers during submaximal cycling exercise. *Eur J Appl Physiol Occup Physiol*, 65(4), 360-364.
- Allemeier, C. A., Fry, A. C., Johnson, P., Hikida, R. S., Hagerman, F. C., & Staron, R. S. (1994). Effects of sprint cycle training on human skeletal muscle. *J Appl Physiol (1985)*, 77(5), 2385-2390.
- Allen, D. G., Lamb, G. D., & Westerblad, H. (2008a). Impaired calcium release during fatigue. *J Appl Physiol (1985)*, 104(1), 296-305. doi: 00908.2007 [pii]
10.1152/jappphysiol.00908.2007
- Allen, D. G., Lamb, G. D., & Westerblad, H. (2008b). Skeletal muscle fatigue: cellular mechanisms. *Physiol Rev*, 88(1), 287-332. doi: 88/1/287 [pii]
10.1152/physrev.00015.2007
- Allen, D. G., & Trajanovska, S. (2012). The multiple roles of phosphate in muscle fatigue. *Front Physiol*, 3, 463. doi: 10.3389/fphys.2012.00463
- Amann, M. (2011). Central and peripheral fatigue: interaction during cycling exercise in humans. *Med Sci Sports Exerc*, 43(11), 2039-2045. doi: 10.1249/MSS.0b013e31821f59ab
- Amann, M., Romer, L. M., Subudhi, A. W., Pegelow, D. F., & Dempsey, J. A. (2007). Severity of arterial hypoxaemia affects the relative contributions of peripheral muscle fatigue to exercise performance in healthy humans. *J Physiol*, 581(Pt 1), 389-403. doi: jphysiol.2007.129700 [pii]
10.1113/jphysiol.2007.129700

- Ashley, C. C., Mulligan, I. P., & Lea, T. J. (1991). Ca²⁺ and activation mechanisms in skeletal muscle. *Q Rev Biophys*, 24(1), 1-73.
- Baar, K. (2014). Nutrition and the adaptation to endurance training. *Sports Med*, 44 Suppl 1, S5-12. doi: 10.1007/s40279-014-0146-1
- Bailey, S. J., Vanhatalo, A., DiMenna, F. J., Wilkerson, D. P., & Jones, A. M. (2011). Fast-start strategy improves VO₂ kinetics and high-intensity exercise performance. *Med Sci Sports Exerc*, 43(3), 457-467. doi: 10.1249/MSS.0b013e3181ef3dce
- Bailey, S. J., Vanhatalo, A., Wilkerson, D. P., Dimenna, F. J., & Jones, A. M. (2009a). Optimizing the "priming" effect: influence of prior exercise intensity and recovery duration on O₂ uptake kinetics and severe-intensity exercise tolerance. *J Appl Physiol (1985)*, 107(6), 1743-1756. doi: 00810.2009 [pii]
10.1152/jappphysiol.00810.2009
- Bailey, S. J., Wilkerson, D. P., Dimenna, F. J., & Jones, A. M. (2009b). Influence of repeated sprint training on pulmonary O₂ uptake and muscle deoxygenation kinetics in humans. *J Appl Physiol (1985)*, 106(6), 1875-1887. doi: 00144.2009 [pii]
10.1152/jappphysiol.00144.2009 [doi]
- Bailey, S. J., Winyard, P., Vanhatalo, A., Blackwell, J. R., Dimenna, F. J., Wilkerson, D. P., et al. (2009c). Dietary nitrate supplementation reduces the O₂ cost of low-intensity exercise and enhances tolerance to high-intensity exercise in humans. *J Appl Physiol (1985)*, 107(4), 1144-1155. doi: 00722.2009 [pii]
10.1152/jappphysiol.00722.2009
- Bangsbo, J., Graham, T. E., Kiens, B., & Saltin, B. (1992). Elevated muscle glycogen and anaerobic energy production during exhaustive exercise in man. *J Physiol*, 451, 205-227.
- Bangsbo, J., Gunnarsson, T. P., Wendell, J., Nybo, L., & Thomassen, M. (2009). Reduced volume and increased training intensity elevate muscle Na⁺-K⁺ pump alpha₂-subunit expression as well as short- and long-term

- work capacity in humans. *J Appl Physiol* (1985), 107(6), 1771-1780. doi: 00358.2009 [pii]
10.1152/jappphysiol.00358.2009
- Barker, T., Poole, D. C., Noble, M. L., & Barstow, T. J. (2006). Human critical power-oxygen uptake relationship at different pedalling frequencies. *Exp Physiol*, 91(3), 621-632. doi: expphysiol.2005.032789 [pii]
10.1113/expphysiol.2005.032789
- Barnett, C., Carey, M., Proietto, J., Cerin, E., Febbraio, M. A., & Jenkins, D. (2004). Muscle metabolism during sprint exercise in man: influence of sprint training. *J Sci Med Sport*, 7(3), 314-322.
- Baron, B., Noakes, T. D., Dekerle, J., Moullan, F., Robin, S., Matran, R., et al. (2008). Why does exercise terminate at the maximal lactate steady state intensity? *Br J Sports Med*, 42(10), 828-833. doi: bjsm.2007.040444 [pii]
10.1136/bjsm.2007.040444
- Barstow, T. J., Lamarra, N., & Whipp, B. J. (1990). Modulation of muscle and pulmonary O₂ uptakes by circulatory dynamics during exercise. *J Appl Physiol* (1985), 68(3), 979-989.
- Barstow, T. J., & Mole, P. A. (1991). Linear and nonlinear characteristics of oxygen uptake kinetics during heavy exercise. *J Appl Physiol* (1985), 71(6), 2099-2106.
- Bassett, D. R., Jr., & Howley, E. T. (1997). Maximal oxygen uptake: "classical" versus "contemporary" viewpoints. *Med Sci Sports Exerc*, 29(5), 591-603.
- Bassett, D. R., Jr., & Howley, E. T. (2000). Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc*, 32(1), 70-84.
- Beaver, W. L., Wasserman, K., & Whipp, B. J. (1973). On-line computer analysis and breath-by-breath graphical display of exercise function tests. *J Appl Physiol*, 34(1), 128-132.

- Beaver, W. L., Wasserman, K., & Whipp, B. J. (1986). A new method for detecting anaerobic threshold by gas exchange. *J Appl Physiol* (1985), 60(6), 2020-2027.
- Beltman, J. G., de Haan, A., Haan, H., Gerrits, H. L., van Mechelen, W., & Sargeant, A. J. (2004). Metabolically assessed muscle fibre recruitment in brief isometric contractions at different intensities. *Eur J Appl Physiol*, 92(4-5), 485-492. doi: 10.1007/s00421-004-1105-6
- Bergstrom, H. C., Housh, T. J., Cochrane, K. C., Jenkins, N. D., Lewis, R. W., Traylor, D. A., et al. (2013a). An examination of neuromuscular and metabolic fatigue thresholds. *Physiol Meas*, 34(10), 1253-1267. doi: 10.1088/0967-3334/34/10/1253
- Bergstrom, H. C., Housh, T. J., Zuniga, J. M., Camic, C. L., Traylor, D. A., Schmidt, R. J., et al. (2012). A new single work bout test to estimate critical power and anaerobic work capacity. *J Strength Cond Res*, 26(3), 656-663. doi: 10.1519/JSC.0b013e31822b7304
- Bergstrom, H. C., Housh, T. J., Zuniga, J. M., Traylor, D. A., Camic, C. L., Lewis, R. W., Jr., et al. (2013b). The relationships among critical power determined from a 3-min all-out test, respiratory compensation point, gas exchange threshold, and ventilatory threshold. *Res Q Exerc Sport*, 84(2), 232-238.
- Bergstrom, H. C., Housh, T. J., Zuniga, J. M., Traylor, D. A., Lewis, R. W., Camic, C. L., et al. (2013c). Metabolic and neuromuscular responses at critical power from the 3-min all-out test. *Appl Physiol Nutr Metab*, 38(1), 7-13. doi: 10.1139/apnm-2012-0216
- Bergstrom, H. C., Housh, T. J., Zuniga, J. M., Traylor, D. A., Lewis, R. W., Camic, C. L., et al. (2013d). Responses during exhaustive exercise at critical power determined from the 3-min all-out test. *J Sports Sci*, 31(5), 537-545. doi: 10.1080/02640414.2012.738925
- Bergstrom, H. C., Housh, T. J., Zuniga, J. M., Traylor, D. A., Lewis, R. W., Jr., Camic, C. L., et al. (2013e). Mechanomyographic and metabolic responses during continuous cycle ergometry at critical power from the

- 3-min all-out test. *J Electromyogr Kinesiol*, 23(2), 349-355. doi: S1050-6411(12)00204-0 [pii]
10.1016/j.jelekin.2012.11.001
- Bergstrom, H. C., Housh, T. J., Zuniga, J. M., Traylor, D. A., Lewis, R. W., Jr., Camic, C. L., et al. (2014). Differences among estimates of critical power and anaerobic work capacity derived from five mathematical models and the three-minute all-out test. *J Strength Cond Res*, 28(3), 592-600. doi: 10.1519/JSC.0b013e31829b576d
00124278-201403000-00002 [pii]
- Bergstrom, J., Hermansen, L., Hultman, E., & Saltin, B. (1967). Diet, muscle glycogen and physical performance. *Acta Physiol Scand*, 71(2), 140-150. doi: 10.1111/j.1748-1716.1967.tb03720.x
- Billat, V., Petot, H., Karp, J. R., Sarre, G., Morton, R. H., & Mille-Hamard, L. (2013). The sustainability of VO₂max: effect of decreasing the workload. *Eur J Appl Physiol*, 113(2), 385-394. doi: 10.1007/s00421-012-2424-7
- Billat, V., Sirvent, P., Lepretre, P. M., & Koralsztejn, J. P. (2004). Training effect on performance, substrate balance and blood lactate concentration at maximal lactate steady state in master endurance-runners. *Pflugers Arch*, 447(6), 875-883. doi: 10.1007/s00424-003-1215-8
- Bishop, D., & Jenkins, D. G. (1996). The influence of resistance training on the critical power function & time to fatigue at critical power. *Aust J Sci Med Sport*, 28(4), 101-105.
- Bishop, D., Jenkins, D. G., & Howard, A. (1998). The critical power function is dependent on the duration of the predictive exercise tests chosen. *Int J Sports Med*, 19(2), 125-129. doi: 10.1055/s-2007-971894 [doi]
- Black, M. I., Durant, J., Jones, A. M., & Vanhatalo, A. (2014). Critical power derived from a 3-min all-out test predicts 16.1-km road time-trial performance. *Eur J Sport Sci*, 14(3), 217-223. doi: 10.1080/17461391.2013.810306

- Blazev, R., & Lamb, G. D. (1999). Low [ATP] and elevated [Mg²⁺] reduce depolarization-induced Ca²⁺ release in rat skinned skeletal muscle fibres. *J Physiol*, *520 Pt 1*, 203-215. doi: PHY_9561 [pii]
- Bogdanis, G. C. (2012). Effects of physical activity and inactivity on muscle fatigue. *Front Physiol*, *3*, 142. doi: 10.3389/fphys.2012.00142
- Bogdanis, G. C., Nevill, M. E., Boobis, L. H., & Lakomy, H. K. (1996a). Contribution of phosphocreatine and aerobic metabolism to energy supply during repeated sprint exercise. *J Appl Physiol (1985)*, *80(3)*, 876-884.
- Bogdanis, G. C., Nevill, M. E., Boobis, L. H., Lakomy, H. K., & Nevill, A. M. (1995). Recovery of power output and muscle metabolites following 30 s of maximal sprint cycling in man. *J Physiol*, *482 (Pt 2)*, 467-480.
- Bogdanis, G. C., Nevill, M. E., Lakomy, H. K., Graham, C. M., & Louis, G. (1996b). Effects of active recovery on power output during repeated maximal sprint cycling. *Eur J Appl Physiol Occup Physiol*, *74(5)*, 461-469.
- Brickley, G., Doust, J., & Williams, C. A. (2002). Physiological responses during exercise to exhaustion at critical power. *Eur J Appl Physiol*, *88(1-2)*, 146-151. doi: 10.1007/s00421-002-0706-1
- Brickley, G., Green, S., Jenkins, D. G., McEinery, M., Wishart, C., Doust, J. D., et al. (2007). Muscle metabolism during constant- and alternating-intensity exercise around critical power. *Int J Sports Med*, *28(4)*, 300-305. doi: 10.1055/s-2006-924354
- Broxterman, R. M., Ade, C. J., Wilcox, S. L., Schlup, S. J., Craig, J. C., & Barstow, T. J. (2014). Influence of duty cycle on the power-duration relationship: observations and potential mechanisms. *Respir Physiol Neurobiol*, *192*, 102-111. doi: S1569-9048(13)00386-8 [pii]
10.1016/j.resp.2013.11.010

- Bull, A. J., Housh, T. J., Johnson, G. O., & Perry, S. R. (2000). Effect of mathematical modeling on the estimation of critical power. *Med Sci Sports Exerc*, 32(2), 526-530.
- Bundle, M. W., Ernst, C. L., Bellizzi, M. J., Wright, S., & Weyand, P. G. (2006). A metabolic basis for impaired muscle force production and neuromuscular compensation during sprint cycling. *Am J Physiol Regul Integr Comp Physiol*, 291(5), R1457-1464. doi: 00108.2006 [pii]
10.1152/ajpregu.00108.2006
- Bundle, M. W., & Weyand, P. G. (2012). Sprint exercise performance: does metabolic power matter? *Exerc Sport Sci Rev*, 40(3), 174-182. doi: 10.1097/JES.0b013e318258e1c1
00003677-201207000-00010 [pii]
- Burgomaster, K. A., Heigenhauser, G. J., & Gibala, M. J. (2006). Effect of short-term sprint interval training on human skeletal muscle carbohydrate metabolism during exercise and time-trial performance. *J Appl Physiol (1985)*, 100(6), 2041-2047. doi: 01220.2005 [pii]
10.1152/jappphysiol.01220.2005
- Burgomaster, K. A., Howarth, K. R., Phillips, S. M., Rakobowchuk, M., Macdonald, M. J., McGee, S. L., et al. (2008). Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans. *J Physiol*, 586(1), 151-160. doi: jphysiol.2007.142109 [pii]
10.1113/jphysiol.2007.142109 [doi]
- Burgomaster, K. A., Hughes, S. C., Heigenhauser, G. J., Bradwell, S. N., & Gibala, M. J. (2005). Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans. *J Appl Physiol (1985)*, 98(6), 1985-1990. doi: 01095.2004 [pii]
10.1152/jappphysiol.01095.2004
- Burnley, M., Davison, G., & Baker, J. R. (2011). Effects of priming exercise on VO₂ kinetics and the power-duration relationship. *Med Sci Sports Exerc*, 43(11), 2171-2179. doi: 10.1249/MSS.0b013e31821ff26d

- Burnley, M., Doust, J. H., Ball, D., & Jones, A. M. (2002). Effects of prior heavy exercise on VO₂ kinetics during heavy exercise are related to changes in muscle activity. *J Appl Physiol* (1985), 93(1), 167-174. doi: 10.1152/jappphysiol.01217.2001
- Burnley, M., Doust, J. H., & Vanhatalo, A. (2006a). A 3-min all-out test to determine peak oxygen uptake and the maximal steady state. *Med Sci Sports Exerc*, 38(11), 1995-2003. doi: 10.1249/01.mss.0000232024.06114.a6
00005768-200611000-00017 [pii]
- Burnley, M., & Jones, A. M. (2007). Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sport Science*, 7(2), 63-79. doi: 10.1080/17461390701456148
- Burnley, M., Roberts, C. L., Thatcher, R., Doust, J. H., & Jones, A. M. (2006b). Influence of blood donation on O₂ uptake on-kinetics, peak O₂ uptake and time to exhaustion during severe-intensity cycle exercise in humans. *Exp Physiol*, 91(3), 499-509. doi: expphysiol.2005.032805 [pii]
10.1113/expphysiol.2005.032805
- Burnley, M., Vanhatalo, A., Fulford, J., & Jones, A. M. (2010). Similar metabolic perturbations during all-out and constant force exhaustive exercise in humans: a (31)P magnetic resonance spectroscopy study. *Exp Physiol*, 95(7), 798-807. doi: expphysiol.2010.052688 [pii]
10.1113/expphysiol.2010.052688 [doi]
- Burnley, M., Vanhatalo, A., & Jones, A. M. (2012). Distinct profiles of neuromuscular fatigue during muscle contractions below and above the critical torque in humans. *J Appl Physiol* (1985), 113(2), 215-223. doi: jappphysiol.00022.2012 [pii]
10.1152/jappphysiol.00022.2012
- Busse, M. W., Maassen, N., & Konrad, H. (1991). Relation between plasma K⁺ and ventilation during incremental exercise after glycogen depletion and repletion in man. *J Physiol*, 443, 469-476.

- Busso, T., Gimenez, P., & Chatagnon, M. (2010). A comparison of modelling procedures used to estimate the power-exhaustion time relationship. *Eur J Appl Physiol*, *108*(2), 257-263. doi: 10.1007/s00421-009-1213-4
- Cadefau, J., Casademont, J., Grau, J. M., Fernandez, J., Balaguer, A., Vernet, M., et al. (1990). Biochemical and histochemical adaptation to sprint training in young athletes. *Acta Physiol Scand*, *140*(3), 341-351. doi: 10.1111/j.1748-1716.1990.tb09008.x [doi]
- Cady, E. B., Jones, D. A., Lynn, J., & Newham, D. J. (1989). Changes in force and intracellular metabolites during fatigue of human skeletal muscle. *J Physiol*, *418*, 311-325.
- Caiozzo, V. J., Davis, J. A., Ellis, J. F., Azus, J. L., Vandagriff, R., Prietto, C. A., et al. (1982). A comparison of gas exchange indices used to detect the anaerobic threshold. *J Appl Physiol Respir Environ Exerc Physiol*, *53*(5), 1184-1189.
- Calbet, J. A., De Paz, J. A., Garatachea, N., Cabeza de Vaca, S., & Chavarren, J. (2003). Anaerobic energy provision does not limit Wingate exercise performance in endurance-trained cyclists. *J Appl Physiol (1985)*, *94*(2), 668-676. doi: 10.1152/jappphysiol.00128.2002
00128.2002 [pii]
- Caputo, F., & Denadai, B. S. (2008). The highest intensity and the shortest duration permitting attainment of maximal oxygen uptake during cycling: effects of different methods and aerobic fitness level. *Eur J Appl Physiol*, *103*(1), 47-57. doi: 10.1007/s00421-008-0670-5
- Carnevale, T. J., & Gaesser, G. A. (1991). Effects of pedaling speed on the power-duration relationship for high-intensity exercise. *Med Sci Sports Exerc*, *23*(2), 242-246.
- Carter, H., Pringle, J. S., Boobis, L., Jones, A. M., & Doust, J. H. (2004). Muscle glycogen depletion alters oxygen uptake kinetics during heavy exercise. *Med Sci Sports Exerc*, *36*(6), 965-972. doi: 00005768-200406000-00009 [pii]

- Casaburi, R., Storer, T. W., Ben-Dov, I., & Wasserman, K. (1987). Effect of endurance training on possible determinants of VO₂ during heavy exercise. *J Appl Physiol* (1985), 62(1), 199-207.
- Cheetham, M. E., Boobis, L. H., Brooks, S., & Williams, C. (1986). Human muscle metabolism during sprint running. *J Appl Physiol* (1985), 61(1), 54-60.
- Chidnok, W., Dimenna, F. J., Bailey, S. J., Wilkerson, D. P., Vanhatalo, A., & Jones, A. M. (2013a). Effects of pacing strategy on work done above critical power during high-intensity exercise. *Med Sci Sports Exerc*, 45(7), 1377-1385. doi: 10.1249/MSS.0b013e3182860325
- Chidnok, W., Fulford, J., Bailey, S. J., Dimenna, F. J., Skiba, P. F., Vanhatalo, A., et al. (2013b). Muscle metabolic determinants of exercise tolerance following exhaustion: relationship to the "critical power". *J Appl Physiol* (1985), 115(2), 243-250. doi: jappphysiol.00334.2013 [pii] 10.1152/jappphysiol.00334.2013 [doi]
- Clark, I. E., Murray, S. R., & Pettitt, R. W. (2013). Alternative procedures for the three-minute all-out exercise test. *J Strength Cond Res*, 27(8), 2104-2112. doi: 10.1519/JSC.0b013e3182785041
- Clarke, D. C., & Skiba, P. F. (2013). Rationale and resources for teaching the mathematical modeling of athletic training and performance. *Adv Physiol Educ*, 37(2), 134-152. doi: 37/2/134 [pii] 10.1152/advan.00078.2011 [doi]
- Coats, E. M., Rossiter, H. B., Day, J. R., Miura, A., Fukuba, Y., & Whipp, B. J. (2003). Intensity-dependent tolerance to exercise after attaining V(O₂) max in humans. *J Appl Physiol* (1985), 95(2), 483-490. doi: 10.1152/jappphysiol.01142.2002 01142.2002 [pii]
- Cocks, M., Shaw, C. S., Shepherd, S. O., Fisher, J. P., Ranasinghe, A. M., Barker, T. A., et al. (2013). Sprint interval and endurance training are equally effective in increasing muscle microvascular density and eNOS

- content in sedentary males. *J Physiol*, 591(Pt 3), 641-656. doi: jphysiol.2012.239566 [pii]
10.1113/jphysiol.2012.239566
- Coffey, V. G., & Hawley, J. A. (2007). The molecular bases of training adaptation. *Sports Med*, 37(9), 737-763. doi: 3791 [pii]
- Connett, R. J., Honig, C. R., Gayeski, T. E., & Brooks, G. A. (1990). Defining hypoxia: a systems view of VO₂, glycolysis, energetics, and intracellular PO₂. *J Appl Physiol* (1985), 68(3), 833-842.
- Constantini, K., Sabapathy, S., & Cross, T. J. (2014). A single-session testing protocol to determine critical power and W'. *Eur J Appl Physiol*, 114(6), 1153-1161. doi: 10.1007/s00421-014-2827-8
- Costill, D. L., Thomason, H., & Roberts, E. (1973). Fractional utilization of the aerobic capacity during distance running. *Med Sci Sports*, 5(4), 248-252.
- Coyle, E. F. (1999). Physiological determinants of endurance exercise performance. *J Sci Med Sport*, 2(3), 181-189.
- Coyle, E. F., Coggan, A. R., Hemmert, M. K., & Ivy, J. L. (1986). Muscle glycogen utilization during prolonged strenuous exercise when fed carbohydrate. *J Appl Physiol* (1985), 61(1), 165-172.
- Coyle, E. F., Sidossis, L. S., Horowitz, J. F., & Beltz, J. D. (1992). Cycling efficiency is related to the percentage of type I muscle fibers. *Med Sci Sports Exerc*, 24(7), 782-788.
- Dahlstedt, A. J., Katz, A., Wieringa, B., & Westerblad, H. (2000). Is creatine kinase responsible for fatigue? Studies of isolated skeletal muscle deficient in creatine kinase. *FASEB J*, 14(7), 982-990.
- Davis, J. A., Frank, M. H., Whipp, B. J., & Wasserman, K. (1979). Anaerobic threshold alterations caused by endurance training in middle-aged men. *J Appl Physiol Respir Environ Exerc Physiol*, 46(6), 1039-1046.
- Dawson, B., Fitzsimons, M., Green, S., Goodman, C., Carey, M., & Cole, K. (1998). Changes in performance, muscle metabolites, enzymes and fibre

- types after short sprint training. *Eur J Appl Physiol Occup Physiol*, 78(2), 163-169.
- Dawson, M. J., Gadian, D. G., & Wilkie, D. R. (1980). Mechanical relaxation rate and metabolism studied in fatiguing muscle by phosphorus nuclear magnetic resonance. *J Physiol*, 299, 465-484.
- Day, J. R., Rossiter, H. B., Coats, E. M., Skasick, A., & Whipp, B. J. (2003). The maximally attainable VO₂ during exercise in humans: the peak vs. maximum issue. *J Appl Physiol* (1985), 95(5), 1901-1907. doi: 10.1152/jappphysiol.00024.2003
00024.2003 [pii]
- de Koning, J. J., Noordhof, D. A., Uitslag, T. P., Galiart, R. E., Dodge, C., & Foster, C. (2013). An approach to estimating gross efficiency during high-intensity exercise. *Int J Sports Physiol Perform*, 8(6), 682-684. doi: 2011-0202 [pii]
- de Lucas, R. D., Dittrich, N., Junior, R. B., de Souza, K. M., & Guglielmo, L. G. (2012). Is the critical running speed related to the intermittent maximal lactate steady state? *J Sports Sci Med*, 11(1), 89-94.
- Debold, E. P. (2012a). Recent insights into muscle fatigue at the cross-bridge level. *Front Physiol*, 3, 151. doi: 10.3389/fphys.2012.00151
- Debold, E. P. (2012b). Recent insights into the molecular basis of muscular fatigue. *Med Sci Sports Exerc*, 44(8), 1440-1452. doi: 10.1249/MSS.0b013e31824cfd26
- Debold, E. P., Beck, S. E., & Warshaw, D. M. (2008). Effect of low pH on single skeletal muscle myosin mechanics and kinetics. *Am J Physiol Cell Physiol*, 295(1), C173-179. doi: 00172.2008 [pii]
10.1152/ajpccell.00172.2008
- Decorte, N., Lafaix, P. A., Millet, G. Y., Wuyam, B., & Verges, S. (2012). Central and peripheral fatigue kinetics during exhaustive constant-load cycling. *Scand J Med Sci Sports*, 22(3), 381-391. doi: SMS1167 [pii]
10.1111/j.1600-0838.2010.01167.x

- Dekerle, J., Baron, B., Dupont, L., Vanvelcenaher, J., & Pelayo, P. (2003). Maximal lactate steady state, respiratory compensation threshold and critical power. *Eur J Appl Physiol*, 89(3-4), 281-288. doi: 10.1007/s00421-002-0786-y
- Dekerle, J., Barstow, T. J., Regan, L., & Carter, H. (2013). The critical power concept in all-out isokinetic exercise. *J Sci Med Sport*. doi: S1440-2440(13)00197-7 [pii]
10.1016/j.jsams.2013.09.003
- Dekerle, J., Mucci, P., & Carter, H. (2012). Influence of moderate hypoxia on tolerance to high-intensity exercise. *Eur J Appl Physiol*, 112(1), 327-335. doi: 10.1007/s00421-011-1979-z
- DiMenna, F. J., Wilkerson, D. P., Burnley, M., & Jones, A. M. (2008). Influence of priming exercise on pulmonary O₂ uptake kinetics during transitions to high-intensity exercise from an elevated baseline. *J Appl Physiol (1985)*, 105(2), 538-546. doi: 90357.2008 [pii]
10.1152/jappphysiol.90357.2008
- Dittrich, N., de Lucas, R. D., Beneke, R., & Guglielmo, L. G. (2013). Time to Exhaustion at Maximal Lactate Steady State Continuous and Intermittent During Running Exercise. *Int J Sports Physiol Perform*. doi: 2013-0403 [pii]
- Docherty, M., Smith, P. M., & Schroder, K. (2000). Reproducibility of the maximum accumulated oxygen deficit and run time to exhaustion during short-distance running. *Journal of Sports Science*, 18, 331-338.
- Does, M. (2013, 29 August 2013). [Hyperbolic, Linear and constant T ergometry].
- Dotan, R. (2012). Reverse lactate threshold: a novel single-session approach to reliable high-resolution estimation of the anaerobic threshold. *Int J Sports Physiol Perform*, 7(2), 141-151. doi: 2011-0039 [pii]

- Dutka, T. L., & Lamb, G. D. (2004). Effect of low cytoplasmic [ATP] on excitation-contraction coupling in fast-twitch muscle fibres of the rat. *J Physiol*, *560*(Pt 2), 451-468. doi: 10.1113/jphysiol.2004.069112
jphysiol.2004.069112 [pii]
- Edge, J., Eynon, N., McKenna, M. J., Goodman, C. A., Harris, R. C., & Bishop, D. J. (2013). Altering the rest interval during high-intensity interval training does not affect muscle or performance adaptations. *Exp Physiol*, *98*(2), 481-490. doi: expphysiol.2012.067603 [pii]
10.1113/expphysiol.2012.067603
- Egan, B., & Zierath, J. R. (2013). Exercise metabolism and the molecular regulation of skeletal muscle adaptation. *Cell Metab*, *17*(2), 162-184. doi: S1550-4131(12)00503-7 [pii]
10.1016/j.cmet.2012.12.012
- Enoka, R. M., Baudry, S., Rudroff, T., Farina, D., Klass, M., & Duchateau, J. (2011). Unraveling the neurophysiology of muscle fatigue. *J Electromyogr Kinesiol*, *21*(2), 208-219. doi: S1050-6411(10)00165-3 [pii]
10.1016/j.jelekin.2010.10.006
- Esbjornsson, M., Hellsten-Westing, Y., Balsom, P. D., Sjodin, B., & Jansson, E. (1993a). Muscle fibre type changes with sprint training: effect of training pattern. *Acta Physiol Scand*, *149*(2), 245-246. doi: 10.1111/j.1748-1716.1993.tb09618.x [doi]
- Esbjornsson, M., Sylven, C., Holm, I., & Jansson, E. (1993b). Fast twitch fibres may predict anaerobic performance in both females and males. *Int J Sports Med*, *14*(5), 257-263. doi: 10.1055/s-2007-1021174 [doi]
- Fairchild, T. J., Armstrong, A. A., Rao, A., Liu, H., Lawrence, S., & Fournier, P. A. (2003). Glycogen synthesis in muscle fibers during active recovery from intense exercise. *Med Sci Sports Exerc*, *35*(4), 595-602. doi: 10.1249/01.MSS.0000058436.46584.8E
- Ferguson, C., Rossiter, H. B., Whipp, B. J., Cathcart, A. J., Murgatroyd, S. R., & Ward, S. A. (2010). Effect of recovery duration from prior exhaustive

- exercise on the parameters of the power-duration relationship. *J Appl Physiol* (1985), 108(4), 866-874. doi: 91425.2008 [pii]
10.1152/jappphysiol.91425.2008
- Ferguson, C., Whipp, B. J., Cathcart, A. J., Rossiter, H. B., Turner, A. P., & Ward, S. A. (2007). Effects of prior very-heavy intensity exercise on indices of aerobic function and high-intensity exercise tolerance. *J Appl Physiol* (1985), 103(3), 812-822. doi: 01410.2006 [pii]
10.1152/jappphysiol.01410.2006
- Fitts, R. H. (1994). Cellular mechanisms of muscle fatigue. *Physiol Rev*, 74(1), 49-94.
- Francis, J. T., Jr., Quinn, T. J., Amann, M., & LaRoche, D. P. (2010). Defining intensity domains from the end power of a 3-min all-out cycling test. *Med Sci Sports Exerc*, 42(9), 1769-1775. doi: 10.1249/MSS.0b013e3181d612e8
- Fryer, M. W., Owen, V. J., Lamb, G. D., & Stephenson, D. G. (1995). Effects of creatine phosphate and P(i) on Ca²⁺ movements and tension development in rat skinned skeletal muscle fibres. *J Physiol*, 482 (Pt 1), 123-140.
- Fukuba, Y., Miura, A., Endo, M., Kan, A., Yanagawa, K., & Whipp, B. J. (2003). The curvature constant parameter of the power-duration curve for varied-power exercise. *Med Sci Sports Exerc*, 35(8), 1413-1418. doi: 10.1249/01.MSS.0000079047.84364.70
- Gaesser, G. A., Carnevale, T. J., Garfinkel, A., Walter, D. O., & Womack, C. J. (1995). Estimation of critical power with nonlinear and linear models. *Med Sci Sports Exerc*, 27(10), 1430-1438.
- Gaesser, G. A., & Poole, D. C. (1986). Lactate and ventilatory thresholds: disparity in time course of adaptations to training. *J Appl Physiol* (1985), 61(3), 999-1004.
- Gaesser, G. A., & Poole, D. C. (1996). The slow component of oxygen uptake kinetics in humans. *Exerc Sport Sci Rev*, 24, 35-71.

- Gaesser, G. A., & Wilson, L. A. (1988). Effects of continuous and interval training on the parameters of the power-endurance time relationship for high-intensity exercise. *Int J Sports Med*, 9(6), 417-421. doi: 10.1055/s-2007-1025043 [doi]
- Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev*, 81(4), 1725-1789.
- Gastin, P. B. (2001). Energy system interaction and relative contribution during maximal exercise. *Sports Med*, 31(10), 725-741.
- Gejl, K. D., Hvid, L. G., Frandsen, U., Jensen, K., Sahlin, K., & Ortenblad, N. (2014). Muscle glycogen content modifies SR Ca²⁺ release rate in elite endurance athletes. *Med Sci Sports Exerc*, 46(3), 496-505. doi: 10.1249/MSS.0000000000000132
- Gerbino, A., Ward, S. A., & Whipp, B. J. (1996). Effects of prior exercise on pulmonary gas-exchange kinetics during high-intensity exercise in humans. *J Appl Physiol (1985)*, 80(1), 99-107.
- Gibala, M. (2009). Molecular responses to high-intensity interval exercise. *Appl Physiol Nutr Metab*, 34(3), 428-432. doi: h09-046 [pii] 10.1139/H09-046 [doi]
- Gibala, M. J., & Jones, A. M. (2013). Physiological and performance adaptations to high-intensity interval training. *Nestle Nutr Inst Workshop Ser*, 76, 51-60. doi: 000350256 [pii] 10.1159/000350256 [doi]
- Gibala, M. J., Little, J. P., van Essen, M., Wilkin, G. P., Burgomaster, K. A., Safdar, A., et al. (2006). Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. *J Physiol*, 575(Pt 3), 901-911. doi: jphysiol.2006.112094 [pii] 10.1113/jphysiol.2006.112094

- Gibala, M. J., & McGee, S. L. (2008). Metabolic adaptations to short-term high-intensity interval training: a little pain for a lot of gain? *Exerc Sport Sci Rev*, 36(2), 58-63. doi: 10.1097/JES.0b013e318168ec1f00003677-200804000-00003 [pii]
- Gibala, M. J., McGee, S. L., Garnham, A. P., Howlett, K. F., Snow, R. J., & Hargreaves, M. (2009). Brief intense interval exercise activates AMPK and p38 MAPK signaling and increases the expression of PGC-1alpha in human skeletal muscle. *J Appl Physiol* (1985), 106(3), 929-934. doi: 90880.2008 [pii]
10.1152/jappphysiol.90880.2008
- Gollnick, P. D., & Hermansen, L. (1973). Biochemical adaptations to exercise: anaerobic metabolism. *Exerc Sport Sci Rev*, 1, 1-43.
- Grassi, B., Poole, D. C., Richardson, R. S., Knight, D. R., Erickson, B. K., & Wagner, P. D. (1996). Muscle O₂ uptake kinetics in humans: implications for metabolic control. *J Appl Physiol* (1985), 80(3), 988-998.
- Greco, C. C., Carita, R. A., Dekerle, J., & Denadai, B. S. (2012). Effect of aerobic training status on both maximal lactate steady state and critical power. *Appl Physiol Nutr Metab*, 37(4), 736-743. doi: 10.1139/h2012-047 [doi]
- Grossl, T., de Lucas, R. D., de Souza, K. M., & Guglielmo, L. G. (2012). Time to exhaustion at intermittent maximal lactate steady state is longer than continuous cycling exercise. *Appl Physiol Nutr Metab*, 37(6), 1047-1053. doi: 10.1139/h2012-088 [doi]
- Gundersen, K. (2011). Excitation-transcription coupling in skeletal muscle: the molecular pathways of exercise. *Biol Rev Camb Philos Soc*, 86(3), 564-600. doi: 10.1111/j.1469-185X.2010.00161.x
- Hamilton, R. J., Paton, C. D., & Hopkins, W. G. (2006). Effect of high-intensity resistance training on performance of competitive distance runners. *Int J Sports Physiol Perform*, 1(1), 40-49.

- Harris, R. C., Wise, J. A., Price, K. A., Kim, H. J., Kim, C. K., & Sale, C. (2012). Determinants of muscle carnosine content. *Amino Acids*, *43*(1), 5-12. doi: 10.1007/s00726-012-1233-y
- Hauser, T., Bartsch, D., Baumgartel, L., & Schulz, H. (2013). Reliability of maximal lactate-steady-state. *Int J Sports Med*, *34*(3), 196-199. doi: 10.1055/s-0032-1321719 [doi]
- Heigenhauser, G. J., Sutton, J. R., & Jones, N. L. (1983). Effect of glycogen depletion on the ventilatory response to exercise. *J Appl Physiol Respir Environ Exerc Physiol*, *54*(2), 470-474.
- Hellsten-Westling, Y., Balsom, P. D., Norman, B., & Sjodin, B. (1993). The effect of high-intensity training on purine metabolism in man. *Acta Physiol Scand*, *149*(4), 405-412. doi: 10.1111/j.1748-1716.1993.tb09636.x [doi]
- Heubert, R. A., Billat, V. L., Chassaing, P., Bocquet, V., Morton, R. H., Koralsztein, J. P., et al. (2005). Effect of a previous sprint on the parameters of the work-time to exhaustion relationship in high intensity cycling. *Int J Sports Med*, *26*(7), 583-592. doi: 10.1055/s-2004-830335
- Hill, A. V., & Lupton, H. (1923). Muscular exercise, lactic acid, and the supply and utilisation of oxygen. *Quarterly Journal of Medicine*, *16*, 135-171.
- Hill, C. A., Harris, R. C., Kim, H. J., Harris, B. D., Sale, C., Boobis, L. H., et al. (2007). Influence of beta-alanine supplementation on skeletal muscle carnosine concentrations and high intensity cycling capacity. *Amino Acids*, *32*(2), 225-233. doi: 10.1007/s00726-006-0364-4
- Hill, D. W. (1993). The critical power concept. A review. *Sports Med*, *16*(4), 237-254.
- Hill, D. W., Poole, D. C., & Smith, J. C. (2002). The relationship between power and the time to achieve $\dot{V}O_{2max}$. *Med Sci Sports Exerc*, *34*(4), 709-714.
- Hill, D. W., & Smith, J. C. (1993). A comparison of methods of estimating anaerobic work capacity. *Ergonomics*, *36*(12), 1495-1500. doi: 10.1080/00140139308968017

- Hill, D. W., & Smith, J. C. (1999). Determination of critical power by pulmonary gas exchange. *Can J Appl Physiol*, 24(1), 74-86.
- Hill, D. W., & Stevens, E. C. (2005). VO₂ response profiles in severe intensity exercise. *J Sports Med Phys Fitness*, 45(3), 239-247.
- Hill, D. W., Vingren, J. L., & Burdette, S. D. (2013). Effect of plasma donation and blood donation on aerobic and anaerobic responses in exhaustive, severe-intensity exercise. *Appl Physiol Nutr Metab*, 38(5), 551-557. doi: 10.1139/apnm-2012-0361
- Hinckson, E. A., & Hopkins, W. G. (2005). Reliability of time to exhaustion analyzed with critical-power and log-log modeling. *Med Sci Sports Exerc*, 37(4), 696-701. doi: 00005768-200504000-00025 [pii]
- Hogan, M. C., Richardson, R. S., & Haseler, L. J. (1999). Human muscle performance and PCr hydrolysis with varied inspired oxygen fractions: a ³¹P-MRS study. *J Appl Physiol (1985)*, 86(4), 1367-1373.
- Hopker, J., Jobson, S., Carter, H., & Passfield, L. (2010). Cycling efficiency in trained male and female competitive cyclists. *J Sports Sci Med*, 9(2), 332-337.
- Hopkins, W. G. (2000). Analysis of validity by linear regression (Excel spreadsheet). *Sportscience*.
- Hopkins, W. G. (2003). A spreadsheet for analysis of straightforward controlled trials. *Sportscience*, 7.
- Hopkins, W. G. (2004). How to interpret changes in an athletic performance test. *Sportscience*, 8, 1-7.
- Hopkins, W. G. (2010). A Socratic Dialogue on Comparison of Measures. *Sportscience*, 14, 15-21.
- Hopkins, W. G., Edmond, I. M., Hamilton, B. H., Macfarlane, D. J., & Ross, B. H. (1989). Relation between power and endurance for treadmill running of short duration. *Ergonomics*, 32(12), 1565-1571. doi: 10.1080/00140138908966925

- Housh, D. J., Housh, T. J., & Bauge, S. M. (1989). The accuracy of the critical power test for predicting time to exhaustion during cycle ergometry. *Ergonomics*, 32(8), 997-1004. doi: 10.1080/00140138908966860
- Housh, D. J., Housh, T. J., & Bauge, S. M. (1990). A methodological consideration for the determination of critical power and anaerobic work capacity. *Res Q Exerc Sport*, 61(4), 406-409.
- Houston, M. E., & Thomson, J. A. (1977). The response of endurance-adapted adults to intense anaerobic training. *Eur J Appl Physiol Occup Physiol*, 36(3), 207-213.
- Hughes, E. F., Turner, S. C., & Brooks, G. A. (1982). Effects of glycogen depletion and pedaling speed on "anaerobic threshold". *J Appl Physiol Respir Environ Exerc Physiol*, 52(6), 1598-1607.
- Hultman, E. (1995). Fuel selection, muscle fibre. *Proc Nutr Soc*, 54(1), 107-121. doi: S0029665195000139 [pii]
- Iaia, F. M., & Bangsbo, J. (2010). Speed endurance training is a powerful stimulus for physiological adaptations and performance improvements of athletes. *Scand J Med Sci Sports*, 20 Suppl 2, 11-23. doi: 10.1111/j.1600-0838.2010.01193.x
- Iaia, F. M., Thomassen, M., Kolding, H., Gunnarsson, T., Wendell, J., Rostgaard, T., et al. (2008). Reduced volume but increased training intensity elevates muscle Na⁺-K⁺ pump alpha1-subunit and NHE1 expression as well as short-term work capacity in humans. *Am J Physiol Regul Integr Comp Physiol*, 294(3), R966-974. doi: 00666.2007 [pii] 10.1152/ajpregu.00666.2007
- Ivy, J. L., Lee, M. C., Brozinick, J. T., Jr., & Reed, M. J. (1988). Muscle glycogen storage after different amounts of carbohydrate ingestion. *J Appl Physiol (1985)*, 65(5), 2018-2023.
- Ivy, J. L., Res, P. T., Sprague, R. C., & Widzer, M. O. (2003). Effect of a carbohydrate-protein supplement on endurance performance during

exercise of varying intensity. *Int J Sport Nutr Exerc Metab*, 13(3), 382-395.

Jabre, J. F., & Spellman, N. T. (1996). The demonstration of the size principle in humans using macro electromyography and precision decomposition. *Muscle Nerve*, 19(3), 338-341. doi: 10.1002/(SICI)1097-4598(199603)19:3<338::AID-MUS9>3.0.CO;2-E [pii]
10.1002/(SICI)1097-4598(199603)19:3<338::AID-MUS9>3.0.CO;2-E

Jacobs, I., Esbjornsson, M., Sylven, C., Holm, I., & Jansson, E. (1987). Sprint training effects on muscle myoglobin, enzymes, fiber types, and blood lactate. *Med Sci Sports Exerc*, 19(4), 368-374.

Jacobs, R. A., Fluck, D., Bonne, T. C., Burgi, S., Christensen, P. M., Toigo, M., et al. (2013). Improvements in exercise performance with high-intensity interval training coincide with an increase in skeletal muscle mitochondrial content and function. *J Appl Physiol* (1985), 115(6), 785-793. doi: japplphysiol.00445.2013 [pii]
10.1152/japplphysiol.00445.2013

Jansson, E., Esbjornsson, M., Holm, I., & Jacobs, I. (1990). Increase in the proportion of fast-twitch muscle fibres by sprint training in males. *Acta Physiol Scand*, 140(3), 359-363. doi: 10.1111/j.1748-1716.1990.tb09010.x [doi]

Jenkins, D. G., & Quigley, B. M. (1990). Blood lactate in trained cyclists during cycle ergometry at critical power. *Eur J Appl Physiol Occup Physiol*, 61(3-4), 278-283.

Jenkins, D. G., & Quigley, B. M. (1992). Endurance training enhances critical power. *Med Sci Sports Exerc*, 24(11), 1283-1289.

Jenkins, D. G., & Quigley, B. M. (1993). The influence of high-intensity exercise training on the Wlim-Tlim relationship. *Med Sci Sports Exerc*, 25(2), 275-282.

Jeukendrup, A. E. (2004). Carbohydrate intake during exercise and performance. *Nutrition*, 20(7-8), 669-677. doi: 10.1016/j.nut.2004.04.017

S0899900704001169 [pii]

Johansen, L., & Quistorff, B. (2003). 31P-MRS characterization of sprint and endurance trained athletes. *Int J Sports Med*, 24(3), 183-189. doi: 10.1055/s-2003-39085

Johnson, T. M., Sexton, P. J., Placek, A. M., Murray, S. R., & Pettitt, R. W. (2011). Reliability analysis of the 3-min all-out exercise test for cycle ergometry. *Med Sci Sports Exerc*, 43(12), 2375-2380. doi: 10.1249/MSS.0b013e318224cb0f

Jones, A. M., & Carter, H. (2000). The effect of endurance training on parameters of aerobic fitness. *Sports Med*, 29(6), 373-386.

Jones, A. M., & Doust, J. H. (1998). The validity of the lactate minimum test for determination of the maximal lactate steady state. *Med Sci Sports Exerc*, 30(8), 1304-1313.

Jones, A. M., & Poole, D. C. (2005). Oxygen uptake dynamics: from muscle to mouth--an introduction to the symposium. *Med Sci Sports Exerc*, 37(9), 1542-1550. doi: 00005768-200509000-00014 [pii]

Jones, A. M., Vanhatalo, A., Burnley, M., Morton, R. H., & Poole, D. C. (2010). Critical power: implications for determination of $\dot{V}O_{2\max}$ and exercise tolerance. *Med Sci Sports Exerc*, 42(10), 1876-1890. doi: 10.1249/MSS.0b013e3181d9cf7f

Jones, A. M., Wilkerson, D. P., Burnley, M., & Koppo, K. (2003). Prior heavy exercise enhances performance during subsequent perimaximal exercise. *Med Sci Sports Exerc*, 35(12), 2085-2092. doi: 10.1249/01.MSS.0000099108.55944.C4

Jones, A. M., Wilkerson, D. P., DiMenna, F., Fulford, J., & Poole, D. C. (2008). Muscle metabolic responses to exercise above and below the "critical power" assessed using 31P-MRS. *Am J Physiol Regul Integr Comp Physiol*, 294(2), R585-593. doi: 00731.2007 [pii]
10.1152/ajpregu.00731.2007

- Juel, C. (2008). Regulation of pH in human skeletal muscle: adaptations to physical activity. *Acta Physiol (Oxf)*, 193(1), 17-24. doi: APS1840 [pii] 10.1111/j.1748-1716.2008.01840.x [doi]
- Kanehisa, H., & Miyashita, M. (1983). Specificity of velocity in strength training. *Eur J Appl Physiol Occup Physiol*, 52(1), 104-106.
- Karatzafieri, C., Franks-Skiba, K., & Cooke, R. (2008). Inhibition of shortening velocity of skinned skeletal muscle fibers in conditions that mimic fatigue. *Am J Physiol Regul Integr Comp Physiol*, 294(3), R948-955. doi: 00541.2007 [pii] 10.1152/ajpregu.00541.2007
- Katz, A., & Westerblad, H. (2014). Regulation of glycogen breakdown and its consequences for skeletal muscle function after training. *Mamm Genome*. doi: 10.1007/s00335-014-9519-x
- Kelly, J., Vanhatalo, A., Wilkerson, D. P., Wylie, L. J., & Jones, A. M. (2013). Effects of nitrate on the power-duration relationship for severe-intensity exercise. *Med Sci Sports Exerc*, 45(9), 1798-1806. doi: 10.1249/MSS.0b013e31828e885c
- Kendall, K. L., Smith, A. E., Graef, J. L., Fukuda, D. H., Moon, J. R., Beck, T. W., et al. (2009). Effects of four weeks of high-intensity interval training and creatine supplementation on critical power and anaerobic working capacity in college-aged men. *J Strength Cond Res*, 23(6), 1663-1669. doi: 10.1519/JSC.0b013e3181b1fd1f
- Khowaja, A., Choi, I. Y., Seaquist, E. R., & Oz, G. (2014). In vivo Magnetic Resonance Spectroscopy of cerebral glycogen metabolism in animals and humans. *Metab Brain Dis*. doi: 10.1007/s11011-014-9530-7
- Knuth, S. T., Dave, H., Peters, J. R., & Fitts, R. H. (2006). Low cell pH depresses peak power in rat skeletal muscle fibres at both 30 degrees C and 15 degrees C: implications for muscle fatigue. *J Physiol*, 575(Pt 3), 887-899. doi: jphysiol.2006.106732 [pii] 10.1113/jphysiol.2006.106732

- Koga, S., Poole, D. C., Shiojiri, T., Kondo, N., Fukuba, Y., Miura, A., et al. (2005). Comparison of oxygen uptake kinetics during knee extension and cycle exercise. *Am J Physiol Regul Integr Comp Physiol*, 288(1), R212-220. doi: 10.1152/ajpregu.00147.2004
00147.2004 [pii]
- Krogh, A., & Lindhard, J. (1920). The changes in respiration at the transition from work to rest. *J Physiol*, 53(6), 431-439.
- Krustrup, P., Mohr, M., Steensberg, A., Bencke, J., Kjaer, M., & Bangsbo, J. (2006). Muscle and blood metabolites during a soccer game: implications for sprint performance. *Med Sci Sports Exerc*, 38(6), 1165-1174. doi: 10.1249/01.mss.0000222845.89262.cd
00005768-200606000-00020 [pii]
- Krustrup, P., Soderlund, K., Mohr, M., Gonzalez-Alonso, J., & Bangsbo, J. (2004). Recruitment of fibre types and quadriceps muscle portions during repeated, intense knee-extensor exercise in humans. *Pflugers Arch*, 449(1), 56-65. doi: 10.1007/s00424-004-1304-3
- Laursen, P. B., & Jenkins, D. G. (2002). The scientific basis for high-intensity interval training: optimising training programmes and maximising performance in highly trained endurance athletes. *Sports Med*, 32(1), 53-73. doi: 320103 [pii]
- Levine, B. D. (2008). $\dot{V}O_2$ max: what do we know, and what do we still need to know? *J Physiol*, 586(1), 25-34. doi: jphysiol.2007.147629 [pii]
10.1113/jphysiol.2007.147629
- Linnarsson, D. (1974). Dynamics of pulmonary gas exchange and heart rate changes at start and end of exercise. *Acta Physiol Scand Suppl*, 415, 1-68.
- Linnarsson, D., Karlsson, J., Fagraeus, L., & Saltin, B. (1974). Muscle metabolites and oxygen deficit with exercise in hypoxia and hyperoxia. *J Appl Physiol*, 36(4), 399-402.

- Linossier, M. T., Denis, C., Dormois, D., Geysant, A., & Lacour, J. R. (1993). Ergometric and metabolic adaptation to a 5-s sprint training programme. *Eur J Appl Physiol Occup Physiol*, 67(5), 408-414.
- Little, J. P., Safdar, A., Bishop, D., Tarnopolsky, M. A., & Gibala, M. J. (2011). An acute bout of high-intensity interval training increases the nuclear abundance of PGC-1alpha and activates mitochondrial biogenesis in human skeletal muscle. *Am J Physiol Regul Integr Comp Physiol*, 300(6), R1303-1310. doi: ajpregu.00538.2010 [pii]
10.1152/ajpregu.00538.2010 [doi]
- Little, J. P., Safdar, A., Cermak, N., Tarnopolsky, M. A., & Gibala, M. J. (2010a). Acute endurance exercise increases the nuclear abundance of PGC-1alpha in trained human skeletal muscle. *Am J Physiol Regul Integr Comp Physiol*, 298(4), R912-917. doi: 00409.2009 [pii]
10.1152/ajpregu.00409.2009 [doi]
- Little, J. P., Safdar, A., Wilkin, G. P., Tarnopolsky, M. A., & Gibala, M. J. (2010b). A practical model of low-volume high-intensity interval training induces mitochondrial biogenesis in human skeletal muscle: potential mechanisms. *J Physiol*, 588(Pt 6), 1011-1022. doi: jphysiol.2009.181743 [pii]
10.1113/jphysiol.2009.181743 [doi]
- Lloyd, B. B. (1966). The energetics of running: an analysis of world records. *Adv Sci*, 22(103), 515-530.
- Lucia, A., Hoyos, J., & Chicharro, J. L. (2001). Preferred pedalling cadence in professional cycling. *Med Sci Sports Exerc*, 33(8), 1361-1366.
- Lucia, A., Hoyos, J., Perez, M., Santalla, A., & Chicharro, J. L. (2002). Inverse relationship between VO₂max and economy/efficiency in world-class cyclists. *Med Sci Sports Exerc*, 34(12), 2079-2084. doi: 10.1249/01.MSS.0000039306.92778.DF
- MacDougall, J. D., Hicks, A. L., MacDonald, J. R., McKelvie, R. S., Green, H. J., & Smith, K. M. (1998). Muscle performance and enzymatic adaptations to sprint interval training. *J Appl Physiol (1985)*, 84(6), 2138-2142.

- Martin, J. C., Brown, N. A., Anderson, F. C., & Spirduso, W. W. (2000). A governing relationship for repetitive muscular contraction. *J Biomech*, 33(8), 969-974. doi: S0021929000000488 [pii]
- Martin, J. C., Gardner, A. S., Barras, M., & Martin, D. T. (2006). Modeling sprint cycling using field-derived parameters and forward integration. *Med Sci Sports Exerc*, 38(3), 592-597. doi: 10.1249/01.mss.0000193560.34022.04
00005768-200603000-00027 [pii]
- Maughan, R. J., & Leiper, J. B. (1983). Aerobic capacity and fractional utilisation of aerobic capacity in elite and non-elite male and female marathon runners. *Eur J Appl Physiol Occup Physiol*, 52(1), 80-87.
- Maughan, R. J., & Poole, D. C. (1981). The effects of a glycogen-loading regimen on the capacity to perform anaerobic exercise. *Eur J Appl Physiol Occup Physiol*, 46(3), 211-219.
- McCartney, N., Heigenhauser, G. J., & Jones, N. L. (1983). Power output and fatigue of human muscle in maximal cycling exercise. *J Appl Physiol Respir Environ Exerc Physiol*, 55(1 Pt 1), 218-224.
- McClave, S. A., LeBlanc, M., & Hawkins, S. A. (2011). Sustainability of critical power determined by a 3-minute all-out test in elite cyclists. *J Strength Cond Res*, 25(11), 3093-3098. doi: 10.1519/JSC.0b013e318212dafc
- McDaniel, J., Durstine, J. L., Hand, G. A., & Martin, J. C. (2002). Determinants of metabolic cost during submaximal cycling. *J Appl Physiol (1985)*, 93(3), 823-828. doi: 10.1152/jappphysiol.00982.2001
- McKay, B. R., Paterson, D. H., & Kowalchuk, J. M. (2009). Effect of short-term high-intensity interval training vs. continuous training on O₂ uptake kinetics, muscle deoxygenation, and exercise performance. *J Appl Physiol (1985)*, 107(1), 128-138. doi: 90828.2008 [pii]
10.1152/jappphysiol.90828.2008

- McKenna, M. J., Bangsbo, J., & Renaud, J. M. (2008). Muscle K⁺, Na⁺, and Cl⁻ disturbances and Na⁺-K⁺ pump inactivation: implications for fatigue. *J Appl Physiol (1985)*, *104*(1), 288-295. doi: 01037.2007 [pii]
10.1152/jappphysiol.01037.2007 [doi]
- McLean, B. D., Buttifant, D., Gore, C. J., White, K., Liess, C., & Kemp, J. (2013). Physiological and performance responses to a preseason altitude-training camp in elite team-sport athletes. *Int J Sports Physiol Perform*, *8*(4), 391-399. doi: 2012- 0245 [pii]
- McLellan, T. M., & Cheung, K. S. (1992). A comparative evaluation of the individual anaerobic threshold and the critical power. *Med Sci Sports Exerc*, *24*(5), 543-550.
- McNaughton, L., & Thomas, D. (1996). Effects of differing pedalling speeds on the power-duration relationship of high intensity cycle ergometry. *Int J Sports Med*, *17*(4), 287-292. doi: 10.1055/s-2007-972848
- Medbo, J. I., Mohn, A. C., Tabata, I., Bahr, R., Vaage, O., & Sejersted, O. M. (1988). Anaerobic capacity determined by maximal accumulated O₂ deficit. *J Appl Physiol (1985)*, *64*(1), 50-60.
- Medved, I., Brown, M. J., Bjorksten, A. R., & McKenna, M. J. (2004). Effects of intravenous N-acetylcysteine infusion on time to fatigue and potassium regulation during prolonged cycling exercise. *J Appl Physiol (1985)*, *96*(1), 211-217. doi: 10.1152/jappphysiol.00458.2003
00458.2003 [pii]
- Meeusen, R. (2014). Exercise, nutrition and the brain. *Sports Med*, *44 Suppl 1*, S47-56. doi: 10.1007/s40279-014-0150-5
- Metzger, J. M. (1996). Effects of phosphate and ADP on shortening velocity during maximal and submaximal calcium activation of the thin filament in skeletal muscle fibers. *Biophys J*, *70*(1), 409-417. doi: S0006-3495(96)79584-X [pii]
10.1016/S0006-3495(96)79584-X

- Millet, G. Y., & Lepers, R. (2004). Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. *Sports Med*, 34(2), 105-116. doi: 3424 [pii]
- Miura, A., Endo, M., Sato, H., Barstow, T. J., & Fukuba, Y. (2002). Relationship between the curvature constant parameter of the power-duration curve and muscle cross-sectional area of the thigh for cycle ergometry in humans. *Eur J Appl Physiol*, 87(3), 238-244. doi: 10.1007/s00421-002-0623-3
- Miura, A., Kino, F., Kajitani, S., Sato, H., & Fukuba, Y. (1999). The effect of oral creatine supplementation on the curvature constant parameter of the power-duration curve for cycle ergometry in humans. *Jpn J Physiol*, 49(2), 169-174.
- Miura, A., Sato, H., Whipp, B. J., & Fukuba, Y. (2000). The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle ergometry. *Ergonomics*, 43(1), 133-141. doi: 10.1080/001401300184693
- Mohr, M., Krstrup, P., Nielsen, J. J., Nybo, L., Rasmussen, M. K., Juel, C., et al. (2007). Effect of two different intense training regimens on skeletal muscle ion transport proteins and fatigue development. *Am J Physiol Regul Integr Comp Physiol*, 292(4), R1594-1602. doi: 00251.2006 [pii] 10.1152/ajpregu.00251.2006
- Monod, H., & Scherrer, J. (1957). [Capacity for static work in a synergistic muscular group in man]. *C R Seances Soc Biol Fil*, 151(7), 1358-1362.
- Monod, H., & Scherrer, J. (1965). The work capacity of a synergic muscular group. *Ergonomics*, 8, 329-338.
- Moritani, T., Nagata, A., deVries, H. A., & Muro, M. (1981). Critical power as a measure of physical work capacity and anaerobic threshold. *Ergonomics*, 24(5), 339-350. doi: 10.1080/00140138108924856
- Morton, R. H. (1986). A three component model of human bioenergetics. *J Math Biol*, 24(4), 451-466.

- Morton, R. H. (2006). The critical power and related whole-body bioenergetic models. *Eur J Appl Physiol*, 96(4), 339-354. doi: 10.1007/s00421-005-0088-2
- Moseley, L., & Jeukendrup, A. E. (2001). The reliability of cycling efficiency. *Med Sci Sports Exerc*, 33(4), 621-627.
- Murgatroyd, S. R., Ferguson, C., Ward, S. A., Whipp, B. J., & Rossiter, H. B. (2011). Pulmonary O₂ uptake kinetics as a determinant of high-intensity exercise tolerance in humans. *J Appl Physiol* (1985), 110(6), 1598-1606. doi: japplphysiol.01092.2010 [pii]
10.1152/japplphysiol.01092.2010
- Nebelsick-Gullett, L. J., Housh, T. J., Johnson, G. O., & Bauge, S. M. (1988). A comparison between methods of measuring anaerobic work capacity. *Ergonomics*, 31(10), 1413-1419. doi: 10.1080/00140138808966785
- Nevill, A. M., & Greenhaff, P. (1999). Skeletal muscle metabolism during high-intensity exercise in humans. In B. J. Whipp & A. J. Sargeant (Eds.), *Physiological determinants of exercise tolerance in humans* (pp. 49 - 60). London: Portland Press.
- Nevill, M. E., Boobis, L. H., Brooks, S., & Williams, C. (1989). Effect of training on muscle metabolism during treadmill sprinting. *J Appl Physiol* (1985), 67(6), 2376-2382.
- Nicolo, A., & Sacchetti, M. (2014). *Do 3-min all-out test parameters accurately predict competitive cyclist performance in the severe intensity domain?* Paper presented at the World Congress of Cycling Science, Leeds, UK. Oral Retrieved from
- Noakes, T. D., Peltonen, J. E., & Rusko, H. K. (2001). Evidence that a central governor regulates exercise performance during acute hypoxia and hyperoxia. *J Exp Biol*, 204(Pt 18), 3225-3234.
- Noakes, T. D., & St Clair Gibson, A. (2004). Logical limitations to the "catastrophe" models of fatigue during exercise in humans. *Br J Sports Med*, 38(5), 648-649. doi: 10.1136/bjism.2003.009761

38/5/648 [pii]

Noakes, T. D., St Clair Gibson, A., & Lambert, E. V. (2004). From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans. *Br J Sports Med*, 38(4), 511-514. doi: 10.1136/bjism.2003.009860

38/4/511 [pii]

Noordhof, D. A., de Koning, J. J., & Foster, C. (2010). The maximal accumulated oxygen deficit method: a valid and reliable measure of anaerobic capacity? *Sports Med*, 40(4), 285-302. doi: 2 [pii]

10.2165/11530390-000000000-00000

Noordhof, D. A., Vink, A. M., de Koning, J. J., & Foster, C. (2011). Anaerobic capacity: effect of computational method. *Int J Sports Med*, 32(6), 422-428. doi: 10.1055/s-0031-1271676

Overend, T. J., Cunningham, D. A., Paterson, D. H., & Smith, W. D. (1992). Physiological responses of young and elderly men to prolonged exercise at critical power. *Eur J Appl Physiol Occup Physiol*, 64(2), 187-193.

Ozyener, F., Rossiter, H. B., Ward, S. A., & Whipp, B. J. (2001). Influence of exercise intensity on the on- and off-transient kinetics of pulmonary oxygen uptake in humans. *J Physiol*, 533(Pt 3), 891-902. doi: PHY_11851 [pii]

Ozyener, F., Rossiter, H. B., Ward, S. A., & Whipp, B. J. (2003). Negative accumulated oxygen deficit during heavy and very heavy intensity cycle ergometry in humans. *Eur J Appl Physiol*, 90(1-2), 185-190. doi: 10.1007/s00421-003-0870-y

Parra, J., Cadefau, J. A., Rodas, G., Amigo, N., & Cusso, R. (2000). The distribution of rest periods affects performance and adaptations of energy metabolism induced by high-intensity training in human muscle. *Acta Physiol Scand*, 169(2), 157-165. doi: aps730 [pii]

10.1046/j.1365-201x.2000.00730.x [doi]

- Paton, C. D., & Hopkins, W. G. (2001). Tests of cycling performance. *Sports Med*, 31(7), 489-496.
- Pelletier, D. M., Lacerte, G., & Goulet, E. D. (2013). Effects of quercetin supplementation on endurance performance and maximal oxygen consumption: a meta-analysis. *Int J Sport Nutr Exerc Metab*, 23(1), 73-82.
- Poole, D. C., & Gaesser, G. A. (1985). Response of ventilatory and lactate thresholds to continuous and interval training. *J Appl Physiol* (1985), 58(4), 1115-1121.
- Poole, D. C., & Jones, A. M. (2012). Oxygen uptake kinetics. *Compr Physiol*, 2(2), 933-996. doi: 10.1002/cphy.c100072
- Poole, D. C., & Richardson, R. S. (1997). Determinants of oxygen uptake. Implications for exercise testing. *Sports Med*, 24(5), 308-320.
- Poole, D. C., Ward, S. A., Gardner, G. W., & Whipp, B. J. (1988). Metabolic and respiratory profile of the upper limit for prolonged exercise in man. *Ergonomics*, 31(9), 1265-1279. doi: 10.1080/00140138808966766 [doi]
- Poole, D. C., Ward, S. A., & Whipp, B. J. (1990). The effects of training on the metabolic and respiratory profile of high-intensity cycle ergometer exercise. *Eur J Appl Physiol Occup Physiol*, 59(6), 421-429.
- Powers, S. K., Dodd, S., & Garner, R. (1984). Precision of ventilatory and gas exchange alterations as a predictor of the anaerobic threshold. *Eur J Appl Physiol Occup Physiol*, 52(2), 173-177.
- Pringle, J. S., & Jones, A. M. (2002). Maximal lactate steady state, critical power and EMG during cycling. *Eur J Appl Physiol*, 88(3), 214-226. doi: 10.1007/s00421-002-0703-4
- Raja, G., Brau, L., Palmer, T. N., & Fournier, P. A. (2008). Fiber-specific responses of muscle glycogen repletion in fasted rats physically active during recovery from high-intensity physical exertion. *Am J Physiol Regul Integr Comp Physiol*, 295(2), R633-641. doi: 00874.2007 [pii] 10.1152/ajpregu.00874.2007

- Roberts, A. D., Billeter, R., & Howald, H. (1982). Anaerobic muscle enzyme changes after interval training. *Int J Sports Med*, 3(1), 18-21. doi: 10.1055/s-2008-1026055 [doi]
- Romijn, J. A., Coyle, E. F., Sidossis, L. S., Gastaldelli, A., Horowitz, J. F., Endert, E., et al. (1993). Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity and duration. *Am J Physiol*, 265(3 Pt 1), E380-391.
- Rossiter, H. B., Ward, S. A., Doyle, V. L., Howe, F. A., Griffiths, J. R., & Whipp, B. J. (1999). Inferences from pulmonary O₂ uptake with respect to intramuscular [phosphocreatine] kinetics during moderate exercise in humans. *J Physiol*, 518 (Pt 3), 921-932. doi: PHY_9005 [pii]
- Rossiter, H. B., Ward, S. A., Howe, F. A., Kowalchuk, J. M., Griffiths, J. R., & Whipp, B. J. (2002). Dynamics of intramuscular ³¹P-MRS P(i) peak splitting and the slow components of PCr and O₂ uptake during exercise. *J Appl Physiol* (1985), 93(6), 2059-2069. doi: 10.1152/jappphysiol.00446.2002
00446.2002 [pii]
- Roston, W. L., Whipp, B. J., Davis, J. A., Cunningham, D. A., Effros, R. M., & Wasserman, K. (1987). Oxygen uptake kinetics and lactate concentration during exercise in humans. *Am Rev Respir Dis*, 135(5), 1080-1084.
- Sahlin, K., Harris, R. C., Nylind, B., & Hultman, E. (1976). Lactate content and pH in muscle obtained after dynamic exercise. *Pflugers Arch*, 367(2), 143-149.
- Saltin, B., & Karlsson, J. (1971). Muscle glycogen utilisation during work of different intensities. In B. Pernow & B. Saltin (Eds.), *Muscle metabolism during exercise*. (pp. 289-300). New York: Plenum Press.
- Sandiford, S. D., Green, H. J., Duhamel, T. A., Schertzer, J. D., Perco, J. D., & Ouyang, J. (2005). Muscle Na-K-pump and fatigue responses to progressive exercise in normoxia and hypoxia. *Am J Physiol Regul Integr Comp Physiol*, 289(2), R441-R449. doi: 00652.2004 [pii]
10.1152/ajpregu.00652.2004

- Sargeant, A. J. (1994). Human power output and muscle fatigue. *Int J Sports Med*, 15(3), 116-121. doi: 10.1055/s-2007-1021031
- Sargeant, A. J., Hoinville, E., & Young, A. (1981). Maximum leg force and power output during short-term dynamic exercise. *J Appl Physiol Respir Environ Exerc Physiol*, 51(5), 1175-1182.
- Sawyer, B. J., Stokes, D. G., Womack, C. J., Morton, R. H., Weltman, A., & Gaesser, G. A. (2014). Strength training increases endurance time to exhaustion during high-intensity exercise despite no change in critical power. *J Strength Cond Res*, 28(3), 601-609. doi: 10.1519/JSC.0b013e31829e113b
- Scherrer, J., Samson, M., & Paleologue, A. (1954). [Muscular activity and fatigue. I. Ergometric data in human experiments]. *J Physiol (Paris)*, 46(4), 887-916.
- Serpiello, F. R., McKenna, M. J., Bishop, D. J., Aughey, R. J., Caldow, M. K., Cameron-Smith, D., et al. (2012). Repeated sprints alter signaling related to mitochondrial biogenesis in humans. *Med Sci Sports Exerc*, 44(5), 827-834. doi: 10.1249/MSS.0b013e318240067e [doi]
- Shepley, B., MacDougall, J. D., Cipriano, N., Sutton, J. R., Tarnopolsky, M. A., & Coates, G. (1992). Physiological effects of tapering in highly trained athletes. *J Appl Physiol (1985)*, 72(2), 706-711.
- Skiba, P. F., Chidnok, W., Vanhatalo, A., & Jones, A. M. (2012). Modeling the expenditure and reconstitution of work capacity above critical power. *Med Sci Sports Exerc*, 44(8), 1526-1532. doi: 10.1249/MSS.0b013e3182517a80
- Skiba, P. F., Jackman, S., Clarke, D., Vanhatalo, A., & Jones, A. M. (2014). Effect of Work and Recovery Durations on W' Reconstitution during Intermittent Exercise. *Med Sci Sports Exerc*, 46(7), 1433-1440. doi: 10.1249/MSS.0000000000000226
- Smith, J. C., & Hill, D. W. (1993). Stability of parameter estimates derived from the power/time relationship. *Can J Appl Physiol*, 18(1), 43-47.

- Smith, J. C., Stephens, D. P., Hall, E. L., Jackson, A. W., & Earnest, C. P. (1998). Effect of oral creatine ingestion on parameters of the work rate-time relationship and time to exhaustion in high-intensity cycling. *Eur J Appl Physiol Occup Physiol*, 77(4), 360-365. doi: 10.1007/s004210050345
- Sostaric, S. M., Skinner, S. L., Brown, M. J., Sangkabuttra, T., Medved, I., Medley, T., et al. (2006). Alkalosis increases muscle K⁺ release, but lowers plasma [K⁺] and delays fatigue during dynamic forearm exercise. *J Physiol*, 570(Pt 1), 185-205. doi: jphysiol.2005.094615 [pii] 10.1113/jphysiol.2005.094615
- Spurway, N. C. (1992). Aerobic exercise, anaerobic exercise and the lactate threshold. *Br Med Bull*, 48(3), 569-591.
- St Clair Gibson, A., Lambert, E. V., Rauch, L. H., Tucker, R., Baden, D. A., Foster, C., et al. (2006). The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. *Sports Med*, 36(8), 705-722. doi: 3686 [pii]
- St Clair Gibson, A., & Noakes, T. D. (2004). Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. *Br J Sports Med*, 38(6), 797-806. doi: 38/6/797 [pii] 10.1136/bjism.2003.009852
- Stephenson, M. C., Leverton, E., Khoo, E. Y., Poucher, S. M., Johansson, L., Lockton, J. A., et al. (2013). Variability in fasting lipid and glycogen contents in hepatic and skeletal muscle tissue in subjects with and without type 2 diabetes: a 1H and 13C MRS study. *NMR Biomed*, 26(11), 1518-1526. doi: 10.1002/nbm.2985
- Thomas, K., Goodall, S., Stone, M., Howatson, G., Gibson, A. S., & Ansley, L. (2014). Central and Peripheral Fatigue in Male Cyclists after 4-, 20-, and 40-km Time Trials. *Med Sci Sports Exerc*. doi: 10.1249/MSS.0000000000000448

- Tomas, A., Ross, E. Z., & Martin, J. C. (2010). Fatigue during maximal sprint cycling: unique role of cumulative contraction cycles. *Med Sci Sports Exerc*, 42(7), 1364-1369. doi: 10.1249/MSS.0b013e3181cae2ce
- Ulmer, H. V. (1996). Concept of an extracellular regulation of muscular metabolic rate during heavy exercise in humans by psychophysiological feedback. *Experientia*, 52(5), 416-420.
- Valli, G., Cogo, A., Passino, C., Bonardi, D., Morici, G., Fasano, V., et al. (2011). Exercise intolerance at high altitude (5050 m): critical power and W' . *Respir Physiol Neurobiol*, 177(3), 333-341. doi: S1569-9048(11)00197-2 [pii]
10.1016/j.resp.2011.05.014
- van Loon, L. J., Greenhaff, P. L., Constantin-Teodosiu, D., Saris, W. H., & Wagenmakers, A. J. (2001). The effects of increasing exercise intensity on muscle fuel utilisation in humans. *J Physiol*, 536(Pt 1), 295-304. doi: PHY_12382 [pii]
- Vandewalle, H., Peres, G., & Monod, H. (1987). Standard anaerobic exercise tests. *Sports Med*, 4(4), 268-289.
- Vandewalle, H., Vautier, J. F., Kachouri, M., Lechevalier, J. M., & Monod, H. (1997). Work-exhaustion time relationships and the critical power concept. A critical review. *J Sports Med Phys Fitness*, 37(2), 89-102.
- Vanhatalo, A. (2008). *Application of the power-duration relationship to all-out exercise*. (PhD), University of Wales Aberystwyth, Aberystwyth.
- Vanhatalo, A., Doust, J. H., & Burnley, M. (2007). Determination of critical power using a 3-min all-out cycling test. *Med Sci Sports Exerc*, 39(3), 548-555. doi: 10.1249/mss.0b013e31802dd3e6
00005768-200703000-00019 [pii]
- Vanhatalo, A., Doust, J. H., & Burnley, M. (2008a). A 3-min all-out cycling test is sensitive to a change in critical power. *Med Sci Sports Exerc*, 40(9), 1693-1699. doi: 10.1249/MSS.0b013e318177871a

- Vanhatalo, A., Doust, J. H., & Burnley, M. (2008b). Robustness of a 3 min all-out cycling test to manipulations of power profile and cadence in humans. *Exp Physiol*, *93*(3), 383-390. doi: expphysiol.2007.039883 [pii] 10.1113/expphysiol.2007.039883
- Vanhatalo, A., Fulford, J., DiMenna, F. J., & Jones, A. M. (2010a). Influence of hyperoxia on muscle metabolic responses and the power-duration relationship during severe-intensity exercise in humans: a ³¹P magnetic resonance spectroscopy study. *Exp Physiol*, *95*(4), 528-540. doi: expphysiol.2009.050500 [pii] 10.1113/expphysiol.2009.050500 [doi]
- Vanhatalo, A., & Jones, A. M. (2009a). Influence of Creatine Supplementation on the Parameters of the "All-Out Critical Power Test". *Journal of Exercise Science & Fitness*, *7*(1), 9-17. doi: 10.1016/S1728-869X(09)60002-2
- Vanhatalo, A., & Jones, A. M. (2009b). Influence of prior sprint exercise on the parameters of the 'all-out critical power test' in men. *Exp Physiol*, *94*(2), 255-263. doi: expphysiol.2008.045229 [pii] 10.1113/expphysiol.2008.045229 [doi]
- Vanhatalo, A., McNaughton, L. R., Siegler, J., & Jones, A. M. (2010b). Effect of induced alkalosis on the power-duration relationship of "all-out" exercise. *Med Sci Sports Exerc*, *42*(3), 563-570. doi: 10.1249/MSS.0b013e3181b71a4a
- Vanhatalo, A., Poole, D. C., DiMenna, F. J., Bailey, S. J., & Jones, A. M. (2011). Muscle fiber recruitment and the slow component of O₂ uptake: constant work rate vs. all-out sprint exercise. *Am J Physiol Regul Integr Comp Physiol*, *300*(3), R700-707. doi: ajpregu.00761.2010 [pii] 10.1152/ajpregu.00761.2010
- Wagner, P. D. (1992). Gas exchange and peripheral diffusion limitation. *Med Sci Sports Exerc*, *24*(1), 54-58.

- Wagner, P. D. (1996). Determinants of maximal oxygen transport and utilization. *Annu Rev Physiol*, 58, 21-50. doi: 10.1146/annurev.ph.58.030196.000321
- Wagner, P. D. (2011). The critical role of VEGF in skeletal muscle angiogenesis and blood flow. *Biochem Soc Trans*, 39(6), 1556-1559. doi: BST20110646 [pii]
10.1042/BST20110646
- Wasserman, K., Whipp, B. J., Koysl, S. N., & Beaver, W. L. (1973). Anaerobic threshold and respiratory gas exchange during exercise. *J Appl Physiol*, 35(2), 236-243.
- Wergel-Kolmert, U., Agehall, A., Rosenberg, N., & Wohlfart, B. (2001). Day-to-day variation in oxygen consumption at submaximal loads during ergometer cycling by adolescents. *Clin Physiol*, 21(2), 135-140. doi: cph313 [pii]
- Westerblad, H., & Allen, D. G. (1993). The influence of intracellular pH on contraction, relaxation and [Ca²⁺]_i in intact single fibres from mouse muscle. *J Physiol*, 466, 611-628.
- Westerblad, H., & Allen, D. G. (2002). Recent advances in the understanding of skeletal muscle fatigue. *Curr Opin Rheumatol*, 14(6), 648-652.
- Westerblad, H., Allen, D. G., & Lannergren, J. (2002). Muscle fatigue: lactic acid or inorganic phosphate the major cause? *News Physiol Sci*, 17, 17-21.
- Weyand, P. G., Lee, C. S., Martinez-Ruiz, R., Bundle, M. W., Bellizzi, M. J., & Wright, S. (1999). High-speed running performance is largely unaffected by hypoxic reductions in aerobic power. *J Appl Physiol (1985)*, 86(6), 2059-2064.
- Weyand, P. G., Lin, J. E., & Bundle, M. W. (2006). Sprint performance-duration relationships are set by the fractional duration of external force application. *Am J Physiol Regul Integr Comp Physiol*, 290(3), R758-765. doi: 00562.2005 [pii]
10.1152/ajpregu.00562.2005

- Whipp, B. J., Davis, J. A., Torres, F., & Wasserman, K. (1981). A test to determine parameters of aerobic function during exercise. *J Appl Physiol Respir Environ Exerc Physiol*, 50(1), 217-221.
- Whipp, B. J., J., H. D., Stoner, N., Lamarra, N., & Wasserman, K. (1982a). A constant which determines the duration of tolerance to high-intensity work. *Fed Proc*, 41, 1591.
- Whipp, B. J., & Ward, S. A. (2009). Quantifying intervention-related improvements in exercise tolerance. *Eur Respir J*, 33(6), 1254-1260. doi: 33/6/1254 [pii]
10.1183/09031936.001110108
- Whipp, B. J., Ward, S. A., Lamarra, N., Davis, J. A., & Wasserman, K. (1982b). Parameters of ventilatory and gas exchange dynamics during exercise. *J Appl Physiol Respir Environ Exerc Physiol*, 52(6), 1506-1513.
- Whipp, B. J., Ward, S. A., & Rossiter, H. B. (2005). Pulmonary O₂ uptake during exercise: conflating muscular and cardiovascular responses. *Med Sci Sports Exerc*, 37(9), 1574-1585. doi: 00005768-200509000-00018 [pii]
- Whipp, B. J., & Wasserman, K. (1972). Oxygen uptake kinetics for various intensities of constant-load work. *J Appl Physiol*, 33(3), 351-356.
- Wilber, R. L. (2004). *Altitude training and athletic performance*. Champaign, IL: Human Kinetics.
- Wilkerson, D. P., & Jones, A. M. (2006). Influence of initial metabolic rate on pulmonary O₂ uptake on-kinetics during severe intensity exercise. *Respir Physiol Neurobiol*, 152(2), 204-219. doi: S1569-9048(05)00242-9 [pii]
10.1016/j.resp.2005.10.001
- Wilkerson, D. P., Koppo, K., Barstow, T. J., & Jones, A. M. (2004). Effect of work rate on the functional 'gain' of Phase II pulmonary O₂ uptake response to exercise. *Respir Physiol Neurobiol*, 142(2-3), 211-223. doi: 10.1016/j.resp.2004.06.001
S156990480400120X [pii]

- Wilkie, D. R. (1960). Man as a source of mechanical power. *Ergonomics*, 3, 1-8.
- Withers, R. T., Sherman, W. M., Clark, D. G., Esselbach, P. C., Nolan, S. R., Mackay, M. H., et al. (1991). Muscle metabolism during 30, 60 and 90 s of maximal cycling on an air-braked ergometer. *Eur J Appl Physiol Occup Physiol*, 63(5), 354-362.
- Wittenberg, B. A., & Wittenberg, J. B. (1989). Transport of oxygen in muscle. *Annu Rev Physiol*, 51, 857-878. doi: 10.1146/annurev.ph.51.030189.004233
- Zelt, J. G., Hankinson, P. B., Foster, W. S., Williams, C. B., Reynolds, J., Garneys, E., et al. (2014). Reducing the volume of sprint interval training does not diminish maximal and submaximal performance gains in healthy men. *Eur J Appl Physiol*. doi: 10.1007/s00421-014-2960-4