

# **Physiological and Anthropometric Predictors of Mountain Ultra Marathon Performance**

**by**

**Michael James Rogers**

B.Sc. (Hons.), Simon Fraser University, 2016

Thesis Submitted in Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science

in the

Department of Biomedical Physiology and Kinesiology  
Faculty of Science

**© Michael Rogers 2018**

**SIMON FRASER UNIVERSITY**

**Spring 2018**

All rights reserved.

However, in accordance with the *Copyright Act of Canada*, this work may be reproduced, without authorization, under the conditions for Fair Dealing. Therefore, limited reproduction of this work for the purposes of private study, research, education, satire, parody, criticism, review and news reporting is likely to be in accordance with the law, particularly if cited appropriately.

# Approval

**Name:** Michael J. Rogers  
**Degree:** Master of Science  
**Title:** *Physiological and Anthropometric Predictors of Mountain Ultra Marathon Performance*  
**Examining Committee:** Chair: Dawn C. Mackey  
Associate Professor

**Matthew D. White**  
Senior Supervisor  
Associate Professor

---

**Michael L. Walsh**  
Supervisor  
Senior Lecturer

---

**David C. Clarke**  
Supervisor  
Assistant Professor

---

**James D. Cotter**  
External Examiner  
Associate Professor  
School of Physical Education  
University of Otago

---

**Date Defended/Approved:** December 13<sup>th</sup>, 2017

## Ethics Statement

The author, whose name appears on the title page of this work, has obtained, for the research described in this work, either:

- a. human research ethics approval from the Simon Fraser University Office of Research Ethics

or

- b. advance approval of the animal care protocol from the University Animal Care Committee of Simon Fraser University

or has conducted the research

- c. as a co-investigator, collaborator, or research assistant in a research project approved in advance.

A copy of the approval letter has been filed with the Theses Office of the University Library at the time of submission of this thesis or project.

The original application for approval and letter of approval are filed with the relevant offices. Inquiries may be directed to those authorities.

Simon Fraser University Library  
Burnaby, British Columbia, Canada

Update Spring 2016

## Abstract

There is yet to be a resolution of the determinants of mountain ultra marathon (MUM) performance. The aim of this thesis was to contribute to resolving these determinants by measuring aerobic, anaerobic and anthropometric metrics and assessing their association to performance in a 50 km MUM race. It was hypothesized for MUM runners with high aerobic power that greater anaerobic capacity, greater lower limb girths, greater surface-area-to-mass, lower endomorphy and lower body fat percentage (BF%) would give better MUM performance. Thirty-four healthy participants volunteered for this study and were measured for their aerobic power, critical velocity (CV), anaerobic running capacity (D'), Wingate Anaerobic test (WAnT) power, and anthropometric variables. For these MUM runners with an aerobic capacity of  $57.8 \pm 6.2 \text{ ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$  a greater CV predicted a faster finishing time in the MUM race ( $R^2=0.75$ ,  $p<0.001$ ,  $n=12$ ), while WAnT ( $r=-0.59$ ,  $p<0.01$ ,  $n=29$ ) and mass-adjusted surface area ( $r=-0.35$ ,  $p<0.05$ ,  $n=34$ ) was correlated to finishing time. Predictors of hill climb times included CV, body fat percentage and endomorphy ( $0.15 < R^2 < 0.90$ ,  $p < 0.05$ ,  $n=12-27$ ). A combination of physiological and anthropometric variables improved the explanation of variance in MUM finishing time by 7-13%. In conclusion, these results that a greater CV, anaerobic capacity, endomorphy, BF% and mass-adjusted surface area, but not a greater lower-limb girth, may contribute to success in a MUM race.

**Keywords:** Anaerobic capacity; critical velocity; exercise; performance; Somatotypes; ultra marathon

## **Acknowledgements**

Without the guidance I have received from my supervisory committee, Drs. Matthew White, Michael Walsh and David Clarke I would not have been able to complete my thesis. I would also like to thank my laboratory colleagues: Sarabjit Sangha, Prabhjot Singh, Sukhraj Sahota, My Linh Ngo, Olivia Sandberg, Peter Lee, Lauren Rietchel, Corrine Malcom, Lauren Penko, and Matthew Dorton. I would like to thank the Department of Biomedical Physiology and Kinesiology and the amazing staff that has assisted me throughout my thesis including Maggie Yeung, Clare Zheng, King Chao, Joe Woo, Darleen Bemister, Cheri Fiedler and Sophie Dunbar. Finally, I would like to thank my parents, Krista and David, for their enduring support during my graduate degree.

# Table of Contents

Approval.....	ii
Ethics Statement.....	iii
Abstract.....	iv
Acknowledgements.....	v
Table of Contents.....	vi
List of Tables.....	ix
List of Figures.....	xi
List of Acronyms.....	xiv
Glossary.....	xv

<b>Chapter 1. Introduction.....</b>	<b>1</b>
1.1. Coyle's Model of Endurance Performance Ability.....	1
1.1.1. Maximal Aerobic Capacity.....	2
1.1.2. Measures of Fractional Utilization of Aerobic Capacity.....	4
Blood Lactate Dynamics During Exercise.....	4
Prediction of Endurance Performance with Lactate Thresholds.....	5
1.1.3. Running Economy.....	7
1.2. Anaerobic Capacity in Endurance Exercise Performance.....	8
1.2.1. Anaerobic Biochemical Pathways.....	10
1.3. Quantifying Anaerobic Capacity.....	12
1.3.1. Methods of Estimating Anaerobic Capacity.....	12
Maximal Accumulated Oxygen Debt.....	12
The Gross Efficiency Method.....	13
Power-Time Curves.....	14
1.3.2. Applications and Limitations of the Velocity Time Model.....	17
1.3.3. The Wingate Anaerobic Test.....	19
1.3.4. Summary of Candidate Variables for Prediction of MUM Performance.....	21
1.4. Anthropometric Predictors of Endurance Performance.....	21
1.4.1. Impact of Anthropometric Variables on Thermoregulation and Endurance Performance.....	22
Body Mass and Surface-area-to-body-mass Ratio.....	22
Hyperthermia and Athletic Performance.....	23
1.4.2. The Effect of Anthropometric Variables on Anaerobic Capacity.....	25
1.4.3. Somatotypes.....	26
1.5. Central Fatigue and Psychological Factors.....	27
1.6. Rationale.....	28
1.7. Hypotheses.....	29
1.8. Chapter 1 Data.....	31

<b>Chapter 2. Prediction of mountain ultra marathon performance with physiological variables.....</b>	<b>37</b>
2.1. Introduction.....	37
2.2. Methods.....	39
2.2.1. Participants.....	39

2.2.2.	Instrumentation .....	39
2.2.3.	Protocol.....	40
	Critical Velocity Testing.....	40
	Anaerobic Capacity Testing.....	40
	Aerobic Power Testing.....	40
	Mountain Ultra Marathon Course and Conditions.....	41
2.2.4.	Statistical Analysis .....	42
2.3.	Results .....	43
2.3.1.	Laboratory and Race Outcome Measures .....	43
2.3.2.	Prediction of Overall Race Time .....	44
2.3.3.	Prediction of Hill Climb Times .....	44
2.4.	Discussion.....	46
	Methodological Applications for Coaches and Athletes.....	52
	Future directions .....	52
2.5.	Conclusion .....	52
2.6.	Chapter 2 Data.....	53

**Chapter 3. Prediction of mountain ultra marathon performance with anthropometric variables ..... 72**

3.1.	Introduction .....	72
3.2.	Methods .....	74
3.2.1.	Participants .....	74
3.2.2.	Instrumentation .....	75
3.2.3.	Protocol.....	75
	Anthropometric Measurements.....	75
	Mountain Ultra Marathon Course and Conditions.....	75
3.2.4.	Statistical Analysis .....	76
3.3.	Results .....	77
3.3.1.	Anthropometric Outcome Measures .....	77
3.3.2.	Prediction of Overall Race Time .....	77
3.3.3.	Prediction of Hill Climb Times .....	78
3.4.	Discussion.....	78
	Future Directions.....	82
3.5.	Conclusion .....	83
3.6.	Chapter 3 Data.....	84

**Chapter 4. Prediction of mountain ultra marathon performance with anthropometric and physiological variables..... 100**

4.1.	Introduction .....	100
4.2.	Methods .....	101
4.2.1.	Participants, Instrumentation, and Protocol .....	101
4.2.2.	Statistical Analysis .....	101
4.3.	Results .....	102
4.3.1.	Prediction of Overall Race Time .....	102
4.3.2.	Prediction of Hill Climb Times .....	103
4.4.	Discussion.....	103
	Future Directions.....	106
4.5.	Conclusion .....	106
4.6.	Chapter 4 Data.....	107

**References** ..... **113**

Appendix. Statistical Analysis and Figures ..... 125

Appendix Data..... 127

## List of Tables

Table 1.1	Equations for the calculation of gross efficiency.....	31
Table 1.2	Critical power and velocity testing methods .....	32
Table 2.1	Power calculation based on effect sizes for outcome variables .....	53
Table 2.2	Pearson correlation matrix of physiological variables, CV and D' with finishing time; *p<0.05, **p<0.01.....	54
Table 2.3	Pearson correlation matrix of physiological variables, CV and D' with hill 1 climb time; *p<0.05, **p<0.01 .....	55
Table 2.4	Pearson correlation matrix of physiological variables, CV and D' with hill 2 climb time, *p<0.05, **p<0.01 .....	56
Table 2.5	Pearson correlation matrix of physiological variables , CV and D' with hill 3 climb time, *p<0.05, **p<0.01 .....	57
Table 2.6	Multiple univariate linear regression of physiological variables, CV and D' with hill 3 climb time. ....	58
Table 3.1	Participants anthropometric characteristics and age, n=34.....	84
Table 3.2	Effect sizes for main predictor variables .....	85
Table 3.3	Equations for the calculation .....	86
Table 3.4	Pearson correlation matrix of anthropometric variables and finishing time; *p<0.05, **p<0.01, n=34.....	87
Table 3.5	Pearson correlation matrix of anthropometric variables and hill 1 climb time; *p<0.05, **p<0.01, n=28.....	88
Table 3.6	Pearson correlation matrix of anthropometric variables and hill 2 climb time; *p<0.05, **p<0.01, n=28.....	89
Table 3.7	Pearson correlation matrix of anthropometric variables and hill 3 climb time; *p<0.05, **p<0.01, n=28.....	90
Table 4.1	Stepwise multiple univariate linear regression of CV and endomorphy to finishing time. Variable values are unstandardized regression coefficients, n=12. CV = critical velocity. ....	107
Table 4.2	Validation analysis of prediction of MUM finishing time with critical velocity and endomorphy. Values are the unstandardized regression coefficients, n=11 for each iteration (Kohavi 1995).....	108
Table 4.3	Stepwise Multiple univariate linear regression of critical velocity and body fat percentage variables to hill 1 climb time. Variable values are unstandardized regression coefficients, n=12. CV = critical velocity, BF = body fat. ....	109

Table 4.4	Stepwise multiple univariate linear regression of hill 3 climb time and physiological and anthropometric variables. Variable values are unstandardized regression coefficients, n=12. CV = critical velocity, BF = body fat. ....	110
-----------	---	-----

## List of Figures

Figure 1.1	Coyle’s model of endurance performance ability (Coyle 1995). Used with permission from Coyle (1995), Integration of the Physiological Factors Determining Endurance Performance Ability, Figure 2.1. Hypothetical model of the interrelationships of physiological factors determining endurance performance ability. Exercise and Sport Sciences Reviews. Volume 23, issue 1. <a href="https://journals.lww.com/acsm-essr/pages/default.aspx">https://journals.lww.com/acsm-essr/pages/default.aspx</a> . Page 26. .... 34	34
Figure 1.2	Estimation of anaerobic metabolism using the maximal accumulated oxygen deficit method. The left panel shows the relationship between oxygen demand and treadmill speed. The right panel shows how accumulated oxygen deficit can be calculated when both the total oxygen demand and the accumulated oxygen uptake are known (Medbø et al. 1988). Reprinted from Medbo et al. (1998), Anaerobic capacity determined by maximal accumulated O <sub>2</sub> deficit, Figure 1. Principles for determining O <sub>2</sub> deficit. This work is protected under copyright, permission is not required for reproduction here. .... 35	35
Figure 1.3	Power – Time or Velocity – Time relationship as described by the parameters of D’ (m) or Anaerobic Work Capacity (W’, J) and Critical Velocity (CV, m•s <sup>-1</sup> ) or Critical Power (CP, W). The division between moderate and heavy work is denoted here as the Lactate Threshold (LT) (Jones et al. 2010). Jones, Vanhatalo and Burnley (2010), Critical Power: Implications for Determination of VO <sub>2max</sub> and Exercise Tolerance, Figure 2: Schematic of the power–time (P–t) relationship for high-intensity exercise illustrating the location of the LT (synonymous with the GET) relative to CP for healthy, physically active young men. Medicine and Science in Sports and Exercise. Volume 42, Issue 10. <a href="https://journals.lww.com/acsm-msse/pages/default.aspx">https://journals.lww.com/acsm-msse/pages/default.aspx</a> . Page 1878. Used with permission. .... 36	36
Figure 2.1	Race course elevation profile. Hill 1 = Black Mountain, hill 2 = Grouse Mountain, hill 3 = Seymour Grind. .... 59	59
Figure 2.2	Running velocities from the critical velocity (CV) test on the track plotted against the reciprocal of completion times (RCT) for each of the three distances (1200 m, 2400 m and 3600 m). The linear regression equations were used to estimate the CV and D’ for each runner, whereby the slope of the plot gives individual D’ values in meters. Each plot features the data of a single participant. .... 60	60
Figure 2.3	Finishing time plotted as a function of mass-adjusted VO <sub>2MAX</sub> . Regression line equation: Finishing time (min) = -95.7• mass-adjusted VO <sub>2MAX</sub> (L•min <sup>-1</sup> ) + 460.5, p<0.01. n=26. .... 61	61

Figure 2.4	Finishing time plotted as a function of both mass-adjusted WAnT peak power (upper panel) and mass-adjusted WAnT mean power (lower panel); n=29 both panels. Top panel regression line equation: Finishing time (min) = $-0.30 \cdot \text{WAnT PP (W)} + 459.8$ , $p < 0.01$ . .....	62
Figure 2.5	Plot of finishing time as a function of $D'$ ; n=12, $p > 0.05$ . .....	63
Figure 2.6	Finishing time plotted as a function of CV; n=12. Regression line equation: Finishing time (min) = $-0.129.1 \cdot \text{CV (m} \cdot \text{s}^{-1}) + 898.7$ , $p < 0.01$ . The size of the markers are scaled by width to represent the magnitude of $D'$ , where a larger marker area corresponds to a greater $D'$ value. ....	64
Figure 2.7	Residual analysis for the goodness of fit of the first order linear regression model for finishing time plotted as a function critical velocity predicted finishing time. Finishing time residuals = critical velocity predicted finishing time – actual finishing time; Shapiro-Wilk’s analysis ( $p=0.88$ ), n=12.....	65
Figure 2.8	Hill 1 climb time plotted as a function of critical velocity. N =10. Regression line equation: Finishing time (min) = $-23.6 \cdot \text{CV (m} \cdot \text{s}^{-1}) + 186.1$ , $p < 0.01$ . .....	66
Figure 2.9	Residual analysis for the goodness of fit of the first order linear regression model for hill 1 time plotted as a function critical velocity predicted hill 1 climb time. Hill 1 climb time residuals = critical velocity predicted hill 1 climb time – actual hill 1 climb time; Shapiro-Wilk’s analysis ( $p=0.60$ ), n=10. ....	67
Figure 2.10	Hill 2 climb time plotted as a function of $\text{VO}_{2\text{LL}}$ Stage. N =10. Regression line equation: Finishing time (min) = $-0.27 \cdot \text{CV (m} \cdot \text{s}^{-1}) + 90.1$ , $p < 0.01$ . .....	68
Figure 2.11	Residual analysis for the goodness of fit of the first order linear regression model for from the first order regression of hill 2 climb time plotted as a function $\text{VO}_{2\text{LL}}$ Stage predicted hill 2 climb time; hill 2 climb time residuals = $\text{VO}_{2\text{LL}}$ stage predicted hill 2 climb time – actual hill 2 climb time; Shapiro-Wilk’s analysis ( $p=0.14$ ), n=10. ....	69
Figure 2.12	Hill 3 climb time as predicted by a two-variable regression of CV and $\text{VO}_{2\text{LL}}$ Stage; n=10. Regression line equation: Finishing time (min) = $-0.91X + 3.8$ , $p < 0.001$ .....	70
Figure 2.13	Residual analysis for the goodness of fit of the first order linear regression model for from the first order regression of hill 3 climb time plotted as a function CV and $\text{VO}_{2\text{LL}}$ Stage predicted hill 3 climb time; hill 3 climb time residuals = CV and $\text{VO}_{2\text{LL}}$ stage predicted hill 2 climb time (as predicted by equation 1) – actual hill 2 climb time; Shapiro-Wilk’s analysis ( $p=0.02$ ), n=10. ....	71
Figure 3.1	Race course elevation profile. Hill 1 = Black Mountain, hill 2 = Grouse Mountain, hill 3 = Seymour Grind. ....	91

Figure 3.2	First order linear regression of finishing time as a function of body fat percentage (BF%), n=34, p <0.001. Regression line equation: finishing time = 8.1•BF(%) + 290.0. ....	92
Figure 3.3	Residuals of finishing time over the range of predicted finishing times by the first order regression of BF%. Finishing time residuals = BF% predicted finishing time – actual finishing time. n=34, Shapiro-Wilk’s analysis (p=0.17). ....	93
Figure 3.4	First order linear regression of hill 1 climb time as a function of body fat percentage (BF%), n=34, p<0.001. Regression line equation: hill 1 climb time (min) = 1.8•BF(%) + 69.1. ....	94
Figure 3.5	Residuals of hill 1 climb time over the range of predicted hill 1 climb time by the first order regression of BF%. Hill 1 climb time Residuals = BF% predicted hill 1 climb time – actual hill 1 climb time. n=28, Shapiro-Wilk’s analysis (p=0.13). ....	95
Figure 3.6	First order linear regression of hill 2 climb time as a function of endomorphy, n=34, p <0.05. Regression line equation: hill 1 climb time (min) = 6.0•endomorphy + 28.4. ....	96
Figure 3.7	Residuals of hill 2 climb time over the range of predicted hill 2 climb time by the first order regression of endomorphy. Hill 2 climb time residuals = endomorphy predicted hill 2 climb time – actual hill 2 climb time. n=28, Shapiro-Wilk’s analysis (p=0.63). ....	97
Figure 3.8	First order linear regression of hill 3 climb time as a function of body fat percentage (BF%), n=34, p <0.001. Regression line equation: hill 1 climb time (min) = 0.79•BF(%) + 26.8. ....	98
Figure 3.9	Residuals of hill 3 climb time over the range of predicted hill 3 climb time by the first order regression of BF%. Hill 3 climb time residuals = BF% predicted hill 3 climb time – actual hill 3 climb time. n=28, Shapiro-Wilk’s analysis (p=0.22). ....	99
Figure 4.1	First order regression of finishing time as a function finishing time predicted by CV and endomorphy as determined by the leave-one-out validation analysis; n=12, p<0.001. ....	111
Figure 4.2	Residuals from a first order regression of finishing time as a function finishing time predicted by CV and endomorphy as calculated by the leave-one-out validation analysis, n=12. ....	112

## List of Acronyms

AC	Anaerobic Capacity
$a-\bar{v}O_2$	Arterial-Mixed Venous Oxygen Concentration difference
$A_D \cdot m^{-1}$	Surface-area-to-body-mass Ratio
AG	Anaerobic Glycolysis
ATP	Adenosine Triphosphate
CK	Creatine Kinase
CP	Critical Power
CSA	Cross-Sectional Area
CV	Critical Velocity
d.m	Dry Mass
D'	An index of anaerobic capacity in the velocity-time model
GE	Gross Efficiency
HR	Heart Rate
LT	Lactate Threshold
MAOD	Maximal Accumulated Oxygen Deficit
MLSS	Maximal Lactate Steady State
MUM	Mountain Ultra Marathon
OBLA	Onset of Blood Lactate
P-t	Power-time
Paer	Aerobic power production
Pan	Anaerobic power production
PCr	Phosphocreatine
RE	Running Economy
V-t	Velocity-time
$\dot{V}O_{2\text{ MAX}}$	Maximal Rate of Oxygen Consumption
$\dot{V}O_{2\text{ PEAK}}$	Peak Rate of Oxygen Consumption
W'	Anaerobic Work Capacity

## Glossary

% $\dot{V}O_{2\text{ MAX}}$ at LT	The $\dot{V}O_2$ as expressed as a percent of their maximal $\dot{V}O_2$ at which an increase of blood lactate is elicited (Coyle 1995).
Anaerobic Work Capacity	“[T]he maximal amount of adenosine triphosphate that can be resynthesized by anaerobic metabolism” (Noordhof, de Koning, and Foster 2010) and the stores of any ATP present.
Critical Velocity / Power	The greatest maintainable pace or power output that can be sustained over an extended, theoretically infinite, period of time (Jones et al. 2010).
Functional Abilities	The exercise capabilities of an athlete which are determined by physiological and morphological components (Coyle 1995). There are several abilities which fall under this category including economy of movement, the aerobic capacity or velocity at lactate threshold, gross mechanical economy, and $\dot{V}O_{2\text{ MAX}}$ (Coyle 1995).
Morphological Components	“Anatomical factors describing the structure of muscle, as well as the cardiovascular system” (Coyle 1995). These are composed of five distinct components including muscle capillary density, stroke volume, aerobic enzyme activity, distribution of power output and technique, and muscle fibre type composition (Coyle 1995).
Performance Abilities	Performance abilities are the resultant athletic abilities of several integrated functional abilities (Coyle 1995). There are numerous performance abilities including performance velocity, resistance to movement, performance power, and performance oxygen consumption (Coyle 1995).
Performance Variables	Variables which measure performance in a fitness test to give an index of a physiological process or processes. In this thesis performance variables include critical velocity and D’.
Performance Velocity	The velocity which can maintained in competition for a certain distance (Coyle 1995).
Q <sub>10</sub> Effect (Temperature coefficient)	“A measure of the effect of a 10°C rise in temperature on the velocity of a chemical reaction” (Kent 2006).
Respiratory Compensation Point	The inflection point of minute ventilation when plotted versus $\dot{V}CO_2$ during incremental exercise (Beaver, Wasserman, and Whipp 1986).
Running Economy	The energy cost requirement for a movement of a set distance, generally described in the units of mL O <sub>2</sub> •kg <sup>-1</sup> •km <sup>-1</sup> (Bassett and Howley 2000).

Somatotyping

The characterization of body types into relative components of endomorphy, ectomorphy and mesomorphy.

$\dot{V}O_{2\text{ MAX}}$

The highest rate of oxygen consumption which can be reached during exercise (Hill and Lupton 1923).

$\dot{V}O_{2\text{ PEAK}}$

The highest rate of oxygen consumption reached given a specific condition or exercise modality (Day et al. 2003).

# **Chapter 1.**

## **Introduction**

Mountain ultra marathons (MUM) are longer and have more variable terrain than a standard 42-km road marathon (Salah, Verla, and Tonga 2012). These races typically range between 50-160 km in length, include long ascents, as well as descents, and are held on trails that can be rocky, steep and slippery (Salah, Verla, and Tonga 2012). Elevated ambient temperatures and high humidity trapped under tree canopies (Stoutjesdijk and Barkman 2014) can elevate heat stress, making heat dissipation more difficult for runners. Due to these and other stressors, it has not yet been determined which physiological (Coyle 1995) and anthropometric (Knechtle 2014) attributes of MUM runners predict their performance.

The goal of this literature review is to summarize the current scientific evidence on which anthropometric and physiological variables might underlie better performance in MUM running races. At the conclusion of the literature review a rationale is given as well as hypotheses that were tested in the two studies given in this thesis.

### **1.1. Coyle's Model of Endurance Performance Ability**

Coyle's model of endurance performance ability is one suggested explanation of how variables might interact to explain the velocity of an athlete during endurance performance (Coyle 1995). Endurance performance ability is the integration of many factors described in Fig. 1.1. Coyle (1995) split this model into three levels: performance abilities, functional abilities and morphological components (Fig 1.1). In this model, the morphological components represent the underlying mechanisms that determine the functional abilities, while functional abilities are the determinants of the performance abilities that are ultimately suggested to determine running or cycling velocity (Coyle

1995). This model is summarized in Equation 1.1 (Lazzer et al. 2012, Coyle 1995). In this equation, the three primary functional abilities are the maximal aerobic capacity ( $\dot{V}O_{2MAX}$ ), the percentage of  $\dot{V}O_{2MAX}$  at lactate threshold (LT) which represents what  $\dot{V}O_2$  can be maintained during endurance running competition and Running Economy (RE) that gives the metabolic cost of movement.

$$\text{Performance velocity (m}\cdot\text{s}^{-1}) = \dot{V}O_{2MAX} (\text{L}\cdot\text{s}^{-1}) \cdot \% \dot{V}O_{2MAX} \text{ at LT} \cdot \text{RE (m}\cdot\text{L}^{-1}) \dots \text{Equation 1.1}$$

The following sections will discuss these three main functional abilities in detail. Each variable will be discussed both in isolation and in combination with the other variables, exploring each variable's potential strengths and shortcomings in the prediction of MUM performance.

### 1.1.1. Maximal Aerobic Capacity

As the intensity of muscular exercise increases so does the volume of oxygen consumption by the human body (Hill and Lupton 1923). This relationship of oxygen consumption as a function of exercise intensity is linear for submaximal exercise and often plateaus after reaching maximal exercise intensity (Hill and Lupton 1923), however this plateau is less commonly observed in ramp exercise testing (Day et al. 2003). The largest attainable rate of oxygen consumption can be regarded as  $\dot{V}O_{2MAX}$  (Bassett and Howley 2000), whereas  $\dot{V}O_{2PEAK}$  is the maximal rate of oxygen consumption specific to a given exercise modality. Generally,  $\dot{V}O_{2MAX}$  is the appropriate terminology for treadmill testing and  $\dot{V}O_{2PEAK}$  is for cycle ergometer testing, as the latter generally results in a  $\dot{V}O_{2MAX}$  that is 5-20% less than testing on a treadmill (Myers et al. 2009) since less muscle mass is used in cycling than running.

Both central and peripheral factors determine aerobic capacity (Bassett and Howley 2000). Central factors include cardiac output, blood volume, blood oxygen carrying capacity and arteriovenous oxygen ( $a-vO_2$ ) difference (Ekblom et al. 1968). As well, to a lesser extent in elite athletes, minute ventilation is also a determinant of aerobic capacity (Dempsey, Hanson, and Henderson 1984). Peripheral factors include skeletal muscle capillary density (Saltin et al. 1977) and skeletal muscle mitochondrial

content (Holloszy and Coyle 1984). Although cardiac output is thought to be one of the most important factors in determining  $\dot{V}O_{2\text{MAX}}$  (Bassett and Howley 2000), Wagner (2000) has argued that  $\dot{V}O_{2\text{MAX}}$  is determined by an integrated combination of both central and peripheral factors and that the relative importance of each factor is dependent upon conditions such as the individual's fitness level and the exercise environment (Wagner 2000).

A high  $\dot{V}O_{2\text{MAX}}$  provides a clear performance advantage as demonstrated by studies of endurance athletes in a wide array of sports. For example, Ingham et al. (2002) correlated maximal aerobic capacity to the maximal speed attained in 2000 m ergometer rowing for both men ( $r=0.80$ ,  $p<0.001$ ) and women ( $r=0.82$ ,  $p<0.001$ ) (Ingham et al. 2002). Similarly, in cross-country skiing, treadmill determined  $\dot{V}O_{2\text{MAX}}$  was shown to negatively correlate to performance time in a 5.6 km cross-country skiing field test which was performed at about 72% of their relative  $\dot{V}O_{2\text{MAX}}$  (Larsson and Henriksson-Larsén 2005). These correlational studies do not support a cause and effect, but additional investigation comparing endurance performance in participants with either high or low aerobic capacities support the view that  $\dot{V}O_{2\text{MAX}}$  sets the upper limit for the rate of oxygen consumption and therefore gives better endurance performance (Coyle et al. 1983).

The relative importance of  $\dot{V}O_{2\text{MAX}}$  as a determinant of performance remains controversial within the study of mountain ultra marathons and multi-day ultra marathon performance. Maximal aerobic capacity in a multiple regression analysis model (Lazzer et al. 2012) made significant contributions to the prediction of multi-day ultra-trail running performance, improving the explanation of variance by 10%. The model included fractional utilization of  $\dot{V}O_{2\text{MAX}}$  during the race and the energetic cost of running as evaluated both before and after the race (Lazzer et al. 2012). These results agree with the current understanding of  $\dot{V}O_{2\text{MAX}}$  being a prerequisite for better endurance performance. There are, however, some results that do not support  $\dot{V}O_{2\text{MAX}}$  as the main predictor of MUM performance. Gatterer et al. (2013) investigated a group of 16 runners who covered a 305-km distance with >13 km of altitude gain over an 8-day period (Gatterer et al. 2013). Despite a moderate range of maximal aerobic capacity values from 47 to 66.4 mL $\cdot$ kg $^{-1}\cdot$ min $^{-1}$ , no predictive relationship was found between  $\dot{V}O_{2\text{MAX}}$  and finishing time. Furthermore, the importance of  $\dot{V}O_{2\text{MAX}}$  relative to other predictor variables

is reduced within well-trained sub-populations which have homogenous, high  $\dot{V}O_{2MAX}$  values (Bassett and Howley 2000). Since these groups have closely matched  $\dot{V}O_{2MAX}$  values, this matching suggests that fitness metrics or anthropometric characteristics may contribute to the explanation of the variance of MUM performance. Therefore, a study of MUM runners must include not only  $\dot{V}O_{2 MAX}$  but should also incorporate other physiological and anthropometric measures.

### **1.1.2. Measures of Fractional Utilization of Aerobic Capacity**

#### ***Blood Lactate Dynamics During Exercise***

Blood lactate concentration rises with increasing work intensity during muscular exercise (Koyal et al. 1976). Primary observations have described the pattern of blood lactate concentration increase both in step increases of exercise intensity during cycle ergometer exercise and during running (Koyal et al. 1976, Roston et al. 1987). In cycling, lower work rates elicit a small rise in blood lactate from 2-3 mmol•L<sup>-1</sup>, which reaches steady state at that same blood lactate concentration (Roston et al. 1987). As work rates increase, a higher blood lactate concentration will be reached until the onset of fatigue (Roston et al. 1987). A study by Kindermann et al. (1979) tracked blood lactate concentration in elite cross-country skiers over various running velocities (Kindermann, Simon, and Keul 1979). Similarly to Roston et al.'s (1987) findings, a rapid increase in blood lactate was also observed above a threshold intensity (Kindermann, Simon, and Keul 1979, Roston et al. 1987).

Different terms have been used to describe the rise of blood lactate concentration during exercise. Previously, the onset of the rise of blood lactate concentration has been described as the “aerobic threshold” which describes a rise of blood lactate concentration from a resting concentration to 2 mmol•L<sup>-1</sup> during exercise (Kindermann, Simon, and Keul 1979). The “anaerobic threshold” describes the attainment of a concentration of 4 mmol•L<sup>-1</sup> of lactate during exercise (Kindermann, Simon, and Keul 1979). These two points give a two-threshold model of which the “aerobic threshold” and “anaerobic threshold” delineate approximate points between different intensities of exercise, with the second “anaerobic threshold” said to separate moderate and heavy intensity exercise (Binder et al. 2008). A recent review by Binder et

al. (2008) has argued in favour of this two threshold model; however, the second threshold might be better described as either the maximal lactate steady state (MLSS), or the onset of blood lactate (OBLA) (Binder et al. 2008). The MLSS is denoted as the highest steady-state blood lactate concentration which is reached by an athlete during exercise (Billat et al. 2003). For clarity within this thesis, the aerobic threshold will be referred to as the first lactate threshold ( $LT_1$ ) and the anaerobic threshold as the OBLA. It is of note that Cabanac and White (1995) and White and Cabanac (1996) present evidence, as reviewed by White (2006), that the second inflection point is a respiratory compensation point (White 2006, White and Cabanac 1995, 1996) or a neurogenic threshold for pulmonary ventilation (White 2006), and that this is a thermoregulatory response independent of changes in blood lactate concentration as others have shown (Glass et al. 1997).

### ***Prediction of Endurance Performance with Lactate Thresholds***

Previous studies observed a predictive relationship between  $LT_1$  and OBLA and endurance performance. For example, the oxygen consumption at both  $LT_1$  and OBLA predicted marathon performance and velocity in a group of distance runners (Tanaka and Matsuura 1984). This study did not restrict its investigation only to  $\dot{V}O_2$  at  $LT_1$  ( $\dot{V}O_{2LT1}$ ) and  $\dot{V}O_2$  at OBLA ( $\dot{V}O_{2OBLA}$ ) but also included running velocity at which those points were reached to give an index of running economy. Correlational analysis showed that both velocity at  $LT_1$  ( $r=0.78$ ,  $p<0.01$ ) and velocity at OBLA ( $r=0.68$ ,  $P<0.05$ ) were positively correlated with marathon performance (Tanaka and Matsuura 1984). Multiple regression including independent variables of velocity at  $LT_1$ ,  $\% \dot{V}O_{2OBLA} - \% \dot{V}O_{2LT1}$ ,  $\dot{V}O_{2MAX}$ , velocity of a 10-km run, velocity at OBLA and  $\dot{V}O_{2LT1}$  showed that velocity at  $LT_1$  ( $r=0.78$ ,  $p<0.01$ ) significantly predicted performance, and that this prediction was improved by ~25% when  $\% \dot{V}O_{2OBLA} - \% \dot{V}O_{2LT1}$  was added as a predictor (Tanaka and Matsuura 1984). In this study, however, it must be noted that a high collinearity between  $LT_1$  and OBLA might have been present and could explain why one and not the other was entered as the first variable in the multiple regression analysis. In a group of 51 well-trained, middle-aged runners, Takeshima and Tanaka (1995) also found  $\dot{V}O_{2LT1}$  to be predictive of 5-km race ( $r=0.83$ ,  $p<0.05$ ), 10-km race ( $r=0.74$ ,  $p<0.05$ ) and marathon performance ( $r=0.88$ ,  $p<0.05$ ).

The above results emphasize the importance of blood lactate concentrations concerning endurance performance. The rationale again being that those able to reach the highest  $\dot{V}O_2$  at LT1 are at an advantage during a distance running event because exercising at intensities above LT1 is associated with eventual fatigue (Roston et al. 1987). Therefore, in the prediction of MUM endurance performance measures of blood lactate concentration should be included to evaluate its contributions to performance both in isolation and relative to other variables such as  $\dot{V}O_{2MAX}$  and running economy. Section 1.1.3 will further discuss the importance of running economy.

Similar to  $\dot{V}O_{2MAX}$  as a predictor of performance in MUM, the literature is inconsistent concerning the effect of  $\dot{V}O_{2LT1}$  on MUM performance. A group of ten, 35 to 70-year-old mountain marathoners were studied to evaluate the relationship between  $\dot{V}O_{2LT1}$  and race performance (Burtscher, Förster, and Burtscher 2008). The study calculated  $\dot{V}O_{2LT1}$  as the point at which the respiratory exchange ratio remained at 1.0 or higher and compared this value to the  $\dot{V}O_{2LT1}$  calculated based on race performance. This calculation was done using the modified ACSM formulae for  $\dot{V}O_{2LT1}$  determined in a graded aerobic capacity test on a treadmill as given in Equation 2 (Glass and Dwyer 2007, Burtscher, Förster, and Burtscher 2008).

$$\dot{V}O_{2LT1Race} \text{ (mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}\text{)} = 1.1 \text{ (unitless)} [0.2 \text{ (mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}\text{) speed (m} \cdot \text{min}^{-1}\text{)} + (0.9 \text{ (mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}\text{) speed (m} \cdot \text{min}^{-1}\text{)} \times \text{fractional grade (decimal)}\text{)]} + 3.5 \text{ (mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}\text{)}$$

.....Equation 1.2

Based on the strong coefficient of determination of  $R^2=0.98$  between  $\dot{V}O_{2LT1}$  in the laboratory and  $\dot{V}O_{2LT1}$  during the race, the authors concluded  $\dot{V}O_{2LT1}$  “almost completely determines mountain running performance” (Burtscher, Förster, and Burtscher 2008). This study, however, has some aspects of its design that suggests there is an overstatement of the results. Firstly, the study did not take into account that an indirect measure was employed using the ACSM formulae to calculate  $\dot{V}O_{2LT1}$  race. Secondly, it was not reported whether  $\dot{V}O_{2LT1}$  determined in the laboratory aerobic capacity test on a treadmill was predictive of MUM finishing time. Finally, the use of respiratory exchange ratio as a marker of either LT1 or OBLA has been previously criticized as not representing the aforementioned thresholds (Binder et al. 2008). Based

on these shortcomings the results and conclusions of this study must be considered cautiously. Indeed, these findings are contradicted by other results showing no relationship between indices of  $\dot{V}O_{2LT1}$  and finishing time in a MUM (Gatterer et al. 2013). For example, the 305 km, 8-day race described in section 1.1.1 that found no relationship between either the ventilatory threshold or the respiratory compensation point and race finishing time (Gatterer et al. 2013).

This subsection 1.1.2 highlights that although  $\dot{V}O_{2LT1}$  is an established determinant of endurance performance it remains to be resolved how it contributes to the explanation of variance of MUM performance. Consequently, determination of MUM performance should include  $\dot{V}O_{2LT1}$  to better understand its potential role underlying success in these types of competitions.

### **1.1.3. Running Economy**

In addition to an athlete's  $\dot{V}O_{2MAX}$  and  $\dot{V}O_{2LT1}$ , RE has been postulated as an additional factor in long-distance running performance (Bassett and Howley 2000). Running economy can be defined as the energy cost required for an athlete to move a certain distance; this can be described in the units of  $\text{ml O}_2 \cdot \text{kg}^{-1} \cdot \text{km}^{-1}$  (Bassett and Howley 2000, Lazzer et al. 2012). Per kilogram of body mass those with a greater running economy can maintain the same running speed at a lower  $\dot{V}O_2$ . Since this lower  $\dot{V}O_2$  would reduce the proportion of carbohydrate versus fat oxidation (Brooks and Mercier 1994) a greater running economy could also help runners to delay glycogen depletion.

In multi-day trail running, better RE was associated with a small but significant improvement in the prediction of race time when using stepwise multiple linear regression analysis (Lazzer et al. 2012). This study examined not only the pre-race cost of running but also RE before and after each consecutive day of competition (Lazzer et al. 2012). This measurement of RE allowed for the calculation of the mean RE over the course of the three-day race, which consisted of 22, 48 and 20 km laps. The fractional use of  $\dot{V}O_2$  and  $\dot{V}O_{2MAX}$  explained 77% of the variance finishing time and the strength of this association was improved by 4% after adding pre-race RE and by 10% by adding

mean race RE. As summarized by Saunders et al. (2004), factors such as an athlete's anthropometry, physiological factors, running biomechanics and environmental heat stress or altitude can all influence RE (Saunders et al. 2004). Consequently, RE is another variable to consider when investigating MUM performance and therefore an index of RE would be advantageous to include in predicting MUM finishing time. In this thesis the measure of critical velocity as an index of RE will be further discussed in subsection 1.3.1.

## **1.2. Anaerobic Capacity in Endurance Exercise Performance**

Review of the current literature shows that anaerobic metabolism and capacity do not appear to have been considered as determinates of MUM performance, instead there is an emphasis being placed on aerobic variables such as  $\dot{V}O_{2MAX}$  and  $\dot{V}O_{2LT1}$  as determinates of MUM performance (Lazzer et al. 2012, Coyle 1995). As described below in section 1.2.1, this assumption appears to be based on the limited capacity of the anaerobic system for ATP production before fatigue occurs (Gastin 2001). Indeed, the anaerobic system energy contribution for even medium-distance track running of 1500 m to 3000 m has been postulated to be less than 6-14% of total energy transfer (Duffield, Dawson, and Goodman 2005). Consequently, the rationale to assess the role of anaerobic capacity in long distance running events, especially for MUM, appeared to be without support in the literature.

Despite the understanding of the contribution of anaerobic metabolism to energy transfer during exercise, the view and rationale presented here is that anaerobic capacity still warrants investigation within the unique endurance challenges of MUMs. A central reason for this view is the rapidly changing metabolic cost incurred during transitions from level to steep uphill running that are often evident during MUM races (Minetti et al. 2002). These abrupt shifts in exercise intensity are suggested to transiently induce substantial increases in the rate of anaerobic biochemical pathways when the metabolic rate far outweighs the rate that energy that can be supplied aerobically.

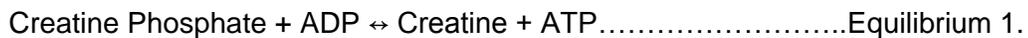
A high race exercise intensity has been reported in both a multistage mountain ultra running races (Gatterer et al. 2013) and multi-day bike stage races (Wirnitzer and Kornexl 2008). In the running ultra marathon, male participants had their heart rate measured over an eight-stage, multi-day, 305-km race with a mean duration of  $50 \pm 8$  h (Gatterer et al. 2013). This study split running intensities into four zones based on heart rate (HR). Below ventilatory threshold was deemed “low intensity,” the ventilatory threshold to the respiratory compensation point was split into “moderate” and “high intensity” HR zones, while above the respiratory compensation point was the “very high” intensity HR zone (Gatterer et al. 2013). During stage 1 of the MUM, which covered 36.3 km and included 1,223 m of elevation gain, the mean HR (SD) was 81(7)% of maximum with ~36% of the stage run at high to very high intensity. The proportion of high to very high intensity dropped to less than 10% throughout the latter stages and days of the MUM race (Gatterer et al. 2013). In the 662 km multistage mountain bike race, the mean finishing time was a sum of  $28 \pm 7$  h from the finishing times in each of 8 stages (Wirnitzer and Kornexl 2008). As for Gatterer et al. (2013), exercise intensity was divided into four laboratory-determined intensity zones (Gatterer et al. 2013). For each intensity zone, the lactate concentrations were recorded and matched with the corresponding HR. “Low intensity” was an HR that corresponded with a blood lactate concentration below 2 mmol lactate $\cdot$ L<sup>-1</sup> lactate, “moderate” between 2-4 mmol $\cdot$ L<sup>-1</sup>, “high” 4-6 mmol $\cdot$ L<sup>-1</sup>, and finally “very high” at above 6 mmol $\cdot$ L<sup>-1</sup> (Wirnitzer and Kornexl 2008). In this stage race, ~27-36% of the overall race was in the high or very high-intensity HR zones, although the proportion of cyclists with HR in this zone dropped to almost zero during the final stages of the race (Wirnitzer and Kornexl 2008). In the first stage of the race, the mean race HR was 84(6)% of the laboratory determined maximal HR and 79(1)% in the race overall (Wirnitzer and Kornexl 2008). These data suggest that anaerobic capacity may play a larger role than previously thought in the initial stages of a long duration, multi-stage running or cycling race as well as during a single day MUM. Furthermore, when considering that athletes may be unable to reach their maximal aerobic capacity after extended fatiguing exercise, it is possible that the intensity of the latter stages of these races were underestimated (Mimura et al. 1988). This evidence supports anaerobic capacity as a candidate independent variable for prediction of performance in MUM runners in shorter, single day MUM races.

### 1.2.1. Anaerobic Biochemical Pathways

Anaerobic capacity can be hypothetically “defined as the maximal amount of adenosine triphosphate (ATP) that can be resynthesized by anaerobic metabolism; that is, mainly phosphocreatine (PCr) hydrolysis and glycolysis” (Noordhof, de Koning, and Foster 2010), however, it seems prudent to also include in this definition the stores of ATP which would be present at the beginning of an exercise bout. Conversely, anaerobic power can be hypothetically defined as the maximal rate at which these above metabolic processes occur (Sahlin, Tonkonogi, and Söderlund 1998). Despite these hypothetical definitions described here and below, however, it is important to emphasize that the measurement of anaerobic capacity and power remains controversial and at best only estimations of either can be made as there are no known direct measures of anaerobic capacity (Noordhof, de Koning, and Foster 2010).

Anaerobic capacity (AC) and power depend on two of the three ATP-generating pathways in the human body: the adenosine triphosphate – creatine phosphate (ATP-PCr) system and glycolysis. The adenosine triphosphate – creatine phosphate pathway is composed of both the local muscular stores of ATP available for hydrolysis and the stores of PCr (Bessman and Carpenter 1985). The ATP-PCr system provides a rapid transfer of energy and a phosphate group from PCr to ADP to give ATP with the equilibrium catalyzed by creatine kinase (CK) (Equilibrium 1) (Bessman and Carpenter 1985).

CK



During high-intensity exercise, PCr rapidly drops from its resting concentration and typically provides energy for short duration, high-intensity efforts of 10-15 s in duration (Gastin 2001). This drop was observed during isometric contractions performed at 66% of 1-RM, in which PCr decreased from a pre-exercise concentration of ~90  $\mu\text{mol}\cdot\text{kg}^{-1}$  dry mass (d.m.) to a post-exercise concentration of ~10  $\mu\text{mol}\cdot\text{kg}^{-1}$ d.m. (Sahlin and Ren 1989). Another example of the decrease of PCr is observed in track sprints 40-100 m in length in which the majority of PCr breakdown occurred during the first 5-7 s of the sprint (Hirvonen et al. 1987). It's notable that the kinetics of the drop in PCr

concentration mirror the rise of oxygen consumption during these transitions of intensity (Haseler et al. 2004), indicating that PCr serves to maintain energy output demand as  $VO_2$  increases. Similar changes in PCr concentrations could be expected during steep uphill sections of a MUM where the change in incline rapidly increases the metabolic demand of movement (Minetti et al. 2002).

During high-intensity exercise, as the rate of pyruvate produced by glycolysis in the cytosol surpasses the rate of its uptake into mitochondria, pyruvate is converted to lactate by the enzyme lactate dehydrogenase (Robergs, Ghiasvand, and Parker 2004). Although historically the resulting “lactic acidosis” and the inhibition of phosphofructokinase (PFK), the rate-limiting enzyme in the glycolytic pathway, by this acidosis has been thought to be a factor contributing to fatigue in anaerobic exercise, the more recent evidence is suggesting otherwise (Spriet 1991, Robergs, Ghiasvand, and Parker 2004). A review of the rate of PFK activity suggests that the enzyme can maintain its rate of activity within the physiological range despite lactic acidosis (Spriet 1991). Furthermore, lactate production from glycogen has been argued to be alkalizing to the muscle cell, helping to mitigate the reduction of skeletal muscle intracellular pH (Robergs, Ghiasvand, and Parker 2004). One concern, however, with an increased rate of glycolysis is depletion of glycogen stores. Depletion of glycogen or glucose is unlikely to occur during a 30-s sprinting event in which glycogen concentration has been observed to fall from ~120 to just ~100 mmol of glycogen•kg<sup>-1</sup> wet weight of skeletal muscle (Withers et al. 1991). In contrast, during a 42.2 km footrace, muscle glycogen concentration has been observed to drop from either normal or glycogen loaded states, which vary from ~110 to 200 mmol of glycogen•kg<sup>-1</sup> wet weight of skeletal muscle (Fairchild et al. 2002), to just 16 mmol•kg<sup>-1</sup> wet weight of muscle (Sherman et al. 1983). Therefore, during longer MUM races glycogen depletion and lack of available lactate as an alkalizing agent are more likely to be evident.

Anaerobic metabolism dominates the relative energy contribution in short-duration, high-intensity exercise. The first thirty seconds of supra-maximal exercise is predominantly supplied by the anaerobic system and is estimated to be about 73(10)% anaerobic and 27(10)% aerobic (Gastin 2001). These energy contribution estimates are given in a review by Gastin et al. (2001) who compiled the results of over 30 studies (Gastin 2001). These 30 studies included those that estimated different energy system

contributions with methods such as invasive measurements, maximal accumulated oxygen deficit (MAOD) and mathematical modeling. This difference in energy system contributions is also evident in untrained, sprint-trained and endurance-trained athletes, although the relative contributions from the anaerobic and aerobic energy transfer systems vary between these training groups (Gastin 2001, Gastin and Lawson 1994). For example, using the MAOD method, it was found that untrained participants had a significantly lower oxygen deficit of (mean (SEM)) 3.52 (0.12) than endurance trained participants who had an oxygen deficit 3.82 (0.30) L (Gastin and Lawson 1994). A significantly lower oxygen deficit was also found in the endurance trained versus sprint trained participants who had an oxygen deficit of 4.82 (0.22) L (Gastin and Lawson 1994). These experiments give insight into the relative anaerobic versus aerobic contributions expected for short-duration, high-intensity efforts which may take place during steep incline sections of a MUM.

### **1.3. Quantifying Anaerobic Capacity**

#### **1.3.1. Methods of Estimating Anaerobic Capacity**

As described above, the possibility exists that the anaerobic system plays an important role in the determination of MUM performance. Estimates of AC include taking muscle biopsies to determine local changes in the concentrations of ATP, PCr, lactate, and glycogen during exercise (Withers et al. 1991). These methods are, however, invasive and have an unverifiable assumption of a set percentage of muscle mass being active during exercise (Withers et al. 1991). Various other non-invasive methods exist for estimating AC, including maximal accumulated oxygen debt, the gross efficiency method, and power-time curves (Noordhof, Skiba, and de Koning 2013). These methods are reviewed below to evaluate which is optimal to use in this study.

#### ***Maximal Accumulated Oxygen Debt***

Maximal accumulated oxygen debt (MAOD) is centered upon the linear relationship between oxygen demand during exercise and exercise intensity or speed as an index of exercise intensity (Noordhof, Skiba, and de Koning 2013, Medbø et al. 1988). This relationship can be established through a series sub-maximal tests (Medbø

et al. 1988). By estimating the total oxygen demand of a supra-maximal exercise bout, the measured  $\dot{V}O_2$  uptake can then be measured in real time and subtracted from the  $\dot{V}O_2$  (Fig 1.2) demand to give the accumulated  $\dot{V}O_2$  deficit (Noordhof, Skiba, and de Koning 2013, Medbø et al. 1988). Medbo et al. (1988) proposed several validation criteria for the calculation of MAOD: 1) that MAOD should level off with increasing exercise duration, 2) that MAOD should “vary independently of the maximal  $O_2$  uptake” (Medbø et al. 1988) 3) that results should be in agreement with existing methods of estimating AC such as blood lactate production, where 1 mol of lactate production was assumed to be equivalent to 1.5 mol of ATP production (Medbø et al. 1988).

The use of MAOD has three main limitations. As stated above, this method assumes a linear relationship between exercise intensity and oxygen demand (Noordhof, Skiba, and de Koning 2013, Medbø et al. 1988). Therefore, it assumes that supra-maximal oxygen demand will be accurately estimated by the submaximal tests. This assumption, however, can be questioned due to the slow  $\dot{V}O_2$  kinetics that occur during supra-maximal intensities (Poole et al. 1988). Secondly, MAOD also has been shown to give markedly different estimates of anaerobic capacity based on the time durations used in each submaximal test (Buck and McNaughton 1999). For example, shorter submaximal tests have been shown to give lower estimates of oxygen debt, whereas longer sub-maximal tests give higher oxygen debt values (Buck and McNaughton 1999). Finally, the reliability of MAOD has been questioned, with Doherty et al. (2000) suggesting MAOD to give unreliable results because the measured output values for repeated MAOD tests did not fall within the 95% limits of agreement (Doherty, Smith, and Schroder 2000).

### ***The Gross Efficiency Method***

The gross efficiency as an estimate of AC method also subtracts the aerobic power from total power to determine the proportion of the work completed anaerobically (Noordhof et al. 2011, Noordhof, Skiba, and de Koning 2013). The calculation of gross efficiency is as follows and is summarized in Table 1.1 (Noordhof et al. 2011). First, gross efficiency is calculated as the ratio of mechanical power output versus metabolic power input as shown in Equation 1.3. Aerobically attributable power input can then be calculated as long as  $\dot{V}O_2$  and the respiratory exchange ratio are measured as shown in

Equations 1.4. and 1.5. Finally, using Equation 1.6., the aerobic power contribution can be calculated for any given power output (Noordhof et al. 2011).

The gross efficiency (GE) method has advantages such as a lower time commitment and being able to show changes in efficiency with prolonged cycling exercise (Noordhof, Skiba, and de Koning 2013). A drawback of this method is that it has found to not be in agreement with other measures of AC such as MAOD (Noordhof et al. 2011).

**Power-Time Curves**

Power – Time (P-t) or Velocity – Time (V-t) curves (Fig 1.3) allow for the mathematical modeling of maximal race pace through the parameters of critical power (CP) and the W' (Jones et al. 2010). The W' is the fixed integral of work that can be completed above critical power and is an index of AC (Fukuba et al. 2003), while CP is the asymptote that is approached with infinitely greater exercise durations (Fukuba et al. 2003). Whereas CP is determined during an activity such as cycling, critical velocity (CV) is determined during running exercise. Likewise, W' is also determined during an activity such as cycling and D' during running exercise when modeling running velocity versus time (V-t) (Jones et al. 2010, Florence and Weir 1997).

CP and W' on an ergometer and CV and D' on a track or treadmill are often established with 3-5 exercise trials that are performed at various fatiguing intensities (Noordhof, Skiba, and de Koning 2013). The power or velocity and duration data are fit to a two-parameter hyperbolic (Equation 8) or linear formula (Equation 9), where t = time in both equations (Jones et al. 2010). In these and the following equations W denotes work, P denotes Power and t represents time.

$(P-CP)t = W'$  .....Equation 8

$P=(W'/t) + CP$  .....Equation 9

Equations 8 and 9

Determination of these parameters, however, is not limited to these two equations as there are an additional 4 other equations which can be used to estimate (Jones et al. 2010):

$$W = W' + CP \cdot t \dots \dots \dots \text{Equation 10}$$

$$T = (W - W') / CP \dots \dots \dots \text{Equation 11}$$

$$W = W' P / (P - CP) \dots \dots \dots \text{Equation 12}$$

$$P = CP \cdot W / (W - W') \dots \dots \dots \text{Equation 13}$$

#### Equations 10-13

These parameters are employed to estimate both the distance that can be run above CV and the maximal pace that can be maintained during long-duration endurance events (Florence and Weir 1997, Bulbulian, Wilcox, and Darabos 1986). Specific examples of the application of this model have been shown in the prediction of ~8 km run time in distance runners with a combination of  $W'$  and CP ( $R^2=0.48$ ) (Bulbulian, Wilcox, and Darabos 1986), and the prediction of marathon time with CV (Florence and Weir 1997). In both these examples a higher  $W'$ , CP and CV were associated with a faster performance time. A study by Florence and Weir (1997) found that a higher CV was a better predictor of faster marathon performance ( $R^2=0.76$ ) than both the  $\dot{V}O_2$  at ventilatory threshold and  $\dot{V}O_{2PEAK}$  in a group of well-trained males and females (Florence and Weir 1997). Furthermore, Nimmerichter et al. (2017) recently showed that  $D'$  can significantly increase the explanation of performance in 5,000 m track running performance from 62 to 73% (Nimmerichter et al. 2017), where a higher  $D'$  was associated with a faster 5,000 m running speed. Based on the previous successful applications of this model, the two components of CV and  $D'$  are well supported by past research outcomes as predictors of performance in shorter duration events and are justifiable as novel predictors of MUM performance.

There are distinct advantages to the Critical Velocity Model using P-t and V-t curves over MAOD and gross efficiency methods. Firstly, the CV method is relatively

easy to administer, this is because the data can be easily collected on a running track or on a treadmill (Jones et al. 2010, Galbraith et al. 2014). Secondly, the running tests allow the estimation of CV, which has been shown to explain 76% of the variance in marathon running performance in a group of well-trained male and female participants as described above (Florence and Weir 1997) as well as explain 77% of 5,000 m track running time, where a higher CV predicted a faster 5,000 m time (Nimmerichter et al. 2017). Critical velocity, like performance velocity in Coyle's model, is a measure that theoretically combines all three of the main components of Coyle's model of endurance performance ability (Equation 1.1) to give an estimate of running time for a fixed distance, including  $\dot{V}O_{2MAX}$ , % of  $\dot{V}O_{2MAX}$  at the lactate threshold, and RE (Coyle 1995). As described in section 1.1., each of these variables is suggested to be a determinant of endurance running performance, therefore a test which incorporates all three of these variables stands to predict finishing time in a MUM. Furthermore, CV might be a superior predictor of MUM performance than other metrics such as the velocity at  $\dot{V}O_{2MAX}$  since it estimates the highest velocity that can be theoretically maintained for a sustained period, whereas velocity at  $\dot{V}O_{2MAX}$  may not represent a maintainable velocity (Florence and Weir 1997, Bulbulian, Wilcox, and Darabos 1986). Finally, V-t modeling versus MAOD is advantageous in that D' is a measure which not only represents an index of anaerobic capacity but also translates this capacity into its potential for horizontal movement as it is a capacity measured in distance. Despite these advantages, V-t curves have yet to be applied in a MUM and may be a valuable tool for helping identify which energy transfer systems predominates during MUM and which help to predict MUM performance. Despite the advantages to the Critical Velocity Model, some limitations for this model also exist. The main limitation is the application of a velocity determined over relatively short duration testing intervals - generally 5 -15 min in duration (Galbraith et al. 2014, Florence and Weir 1997) – to events which can several hours or much longer such as in a MUM event (Salah, Verla, and Tonga 2012, Hoffman 2008) . During this time several physiological changes, such as fuel depletion, could occur as described in the following section.

### 1.3.2. Applications and Limitations of the Velocity Time Model

Studies have previously investigated the physiological basis of CV and CP (Hill and Ferguson 1999, Poole et al. 1988). Running velocities above CV results in a progressive increase in exercise intensity until  $\dot{V}O_{2MAX}$  is reached and fatigue then ensues (Hill and Ferguson 1999). In cycling, increases of hydrogen ion concentration have been observed with work outputs as small as 5% above critical power, with blood lactate increasing until the attainment of  $\dot{V}O_{2MAX}$  (Poole et al. 1988). It has not yet been established whether glycogen-depletion effects CV. The effect of glycogen depletion on CP, however, has been previously tested. In this experiment CP and  $W'$  was determined by the completion of several high intensity exercise trials on a cycle ergometer in both glycogen-depleted and control conditions (Miura et al. 2000). Using the results from the participants'  $\dot{V}O_{2MAX}$  tests these 4 high intensity trails could be individualized to induce fatigue within 2-10 min (Miura et al. 2000).

No difference in CP in was evident between glycogen depleted states vs. normal controls (Miura et al. 2000), despite no differences being found it should be highlighted that the parameters of CP and  $W'$  was determined over a series of tests which lasted between 2 to 10 min. As the authors emphasized, a possible limitation to this study is the application to prolonged exercise (Miura et al. 2000) such as within an MUM, this limitation supported by the generally accepted notion that glycogen depletion will negatively affect endurance exercise (Rapoport 2010). Therefore, despite this study finding no effect of glycogen depletion on CP, the effect of glycogen depletion should never-the-less be considered as a limitation of the Critical Velocity Model in its application to long duration events.

If CV does decrease with glycogen depletion, this decrease may be particularly relevant in races such as MUMs. The CV measured under a normal glycogen state might overestimate the CV of a participant in a glycogen-depleted state towards the end of a MUM race. This change in CV during the course of the race due to glycogen depletion is a possible limitation for the use of CV in testing MUM runners. However, this decrement would not play a role during the beginning sections of the race where glycogen stores would still be sufficient.

The physiological basis of  $W'$  and  $D'$  are yet to be fully understood. As summarized by Jones et al. (2010), and supported by numerous experimental studies (Chidnok et al. 2013, Jones et al. 2010, Miura et al. 2000, Cairns et al. 1997, Millar and Homsher 1990), the size of  $D'$  or  $W'$  is limited by both the depletion of PCr (Chidnok et al. 2013), glycogen stores (Miura et al. 2000), the accumulation of both extracellular  $K^+$  (Cairns et al. 1997) and extracellular inorganic phosphate (Pi) (Millar and Homsher 1990). While the rationale for some of these factors is based on investigations of muscle fatigue in general, as is the case for extracellular  $K^+$  concentration (Cairns et al. 1997), the depletion of PCr (Chidnok et al. 2013) and glycogen (Miura et al. 2000), as well as Pi accumulation (Chidnok et al. 2013) has been studied in the specific context of critical power. For example,  $K^+$  concentration has been assessed experimentally by investigation of muscle fatigue in mouse tissue (Cairns et al. 1997). In this experiment increases in extracellular  $[K^+]$  corresponded with decreased force of tetanic contractions (Cairns et al. 1997). Here a dose-response was demonstrated with increasing extracellular  $[K^+]$  producing progressive reductions in peak tetanic force (Cairns et al. 1997) and this increase of  $[K^+]$  is thought to also play a role in the limitation of  $D'$  or  $W'$ . At the point where the maximal amount of work above CP is reached, PCr is depleted to its lowest observed concentrations whereas Pi concurrently rises to its highest observed concentrations (Chidnok et al. 2013). The rise in Pi is reasoned to negatively affect the relationship between force and calcium concentrations within the muscle, resulting in a lower force of contraction (Millar and Homsher 1990). The authors suggested this was due to a high Pi interfering with the formation of strong cross-bridges during muscle contraction (Millar and Homsher 1990). This accumulation of Pi is yet another factor which may underlie the physiological mechanisms which determine  $W'$  or  $D'$ .

It has also been shown that glycogen depletion reduces  $W'$  during cycling (Miura et al. 2000). Although this reduction has not yet been demonstrated in running exercise, it seems reasonable to suggest that  $D'$  would also be reduced in glycogen depleted running athletes. Therefore, it should be considered that any estimate of  $D'$  might not be a fixed measure and is instead influenced by the glycogen balance of the MUM athletes throughout the race. Despite this limitation,  $D'$ , as an index of AC, is suggested to be an important determinant of performance during the first initial climbs of an MUM where the exercise intensity is high (Minetti et al. 2002) and when it could be presumed the

glycogen stores of the runner are not yet depleted and still adequate to fuel high intensity performance.

The rationale for  $D'$  as a predictor of MUM performance is that those runners with the same CV but larger  $D'$  have an inherent advantage in any portion of the race that is run above CV since these sections would deplete their anaerobic capacity. Furthermore, it is possible that  $D'$  might be restored through restoring PCr stores (Chidnok et al. 2013) during downhill sections of the race during which the energetic cost per unit velocity is lowered (Minetti et al. 2002) and the athlete is maintaining an intensity below critical power, hence allowing for  $D'$  to be subsequently used in the next uphill climb.

It is logical that  $D'$  and CV should be evaluated using the exercise modality that is specific to MUM events. This follows since there are specific adaptations of the skeletal musculature and metabolism to a given type, intensity and duration of exercise as denoted by the specific adaptation to the imposed demand (SAID) principle (Kent 2006). For example, a proposed sports specific fitness test for squash has included running forward from a starting position with a racket and trying to hit balloon targets placed at varying heights (Steininger and Wodick 1987). This is repeated at increasingly fast intervals until exhaustion is reached and this test was found to be a better determinate of performance in squash than treadmill based fitness testing (Steininger and Wodick 1987). Table 1.2 outlines a comparison of several testing methods of  $D'$  and CV, as well as  $W'$  and CP. Of the methods listed in Table 1.2, the same day, track-based timed runs method of 3,600 m, 2,400 m and 1,200 m distances have been found to be a reliable and convenient measure of CV and  $D'$  (Galbraith et al. 2011, Galbraith et al. 2014). Galbraith concluded this method applied in the determination of CV or  $D'$  as opposed to more time-consuming multi-day protocols (Galbraith et al. 2011, Galbraith et al. 2014).

### **1.3.3. The Wingate Anaerobic Test**

The Wingate anaerobic test (WAnT) consists of a 30-s, supramaximal exercise test performed seated on a cycle ergometer. The WAnT has traditionally been viewed as a test of anaerobic performance although some have questioned the relative energy contributions of aerobic and anaerobic systems (Beneke et al. 2002). The aerobic contribution to the WAnT has been estimated to be ~19%, with a ~31% alactic and

~50% lactic contribution of total energy transfer (Beneke et al. 2002). This estimate of aerobic versus anaerobic contribution was made using the measure of  $\dot{V}O_2$  both during and after the WAnT, as well as measures of blood lactate concentration (Beneke et al. 2002). Relative to sprint-trained athletes, who have a greater dependency on anaerobic metabolism during the WAnT, this 19% aerobic contribution to energy transfer during a Wingate test was reported to be greater in endurance athletes (Calbet et al. 2003). In a study comparing the WAnT performance in sprint versus endurance-trained cyclists and using MAOD to calculate anaerobic energy contribution, the sprint-trained athletes were found to have a ~79% anaerobic energy contribution to the total energy cost of the exercise whereas the endurance-trained athletes WAnT test was determined to be ~71% anaerobic contribution to the total energy cost of the exercise (Calbet et al. 2003). These results are supported by an additional study using both invasive measures of muscle biopsies as well as MAOD (Withers et al. 1991). In both the invasive and non-invasive measures, this study found the 30-s maximal cycling test to have a 72% anaerobic metabolism contribution to the total energy cost of the exercise (Withers et al. 1991). Based on these studies, although there are aerobic contributions to the total energy cost of the exercise present in the WAnT, but the evidence supports that this test is predominantly anaerobic and therefore a suitable candidate for the measurement of anaerobic capacity of MUM runners.

There are several reasons why WAnT warrants investigation for prediction of MUM performance. The WAnT is methodologically advantageous because it requires only a single visit to the testing facility, features high reliability (Jaafar et al. 2014), and minimal time commitment. Studies of 16 college-aged males have shown intra-class correlations for peak power of 0.98 and mean power of 0.97 (Jaafar et al. 2014). These qualities make WAnT ideal for further investigation because if it correlates to performance, then it could represent an evaluation that athletes, coaches or organizers could apply to assist in the prediction of MUM performance.

Several studies have used the WAnT to predict running (Perez-Gomez et al. 2008, Yoshida et al. 1990) and cycling performance (Davison et al. 2000, Inoue et al. 2012). Previously, correlational analysis has found that a higher Wingate mean power was a predictor of a faster simulated hill climb time in cycling (Davison et al. 2000),

accounting for 81% of the variance of the 6-km hill climb time and 85% of 1-km hill climb time. In running performance WAnT peak power and mean power has been correlated to various distances of 30 m running time ( $r=-0.72$ ,  $p<0.05$ ) (Perez-Gomez et al. 2008), 300 m running time ( $-0.70<r<-0.74$ ,  $p<0.05$ ) (Perez-Gomez et al. 2008) and 800 m running velocity ( $0.54<r<0.59$ ,  $p<0.05$ ) (Yoshida et al. 1990). These previous applications support the use of WAnT in further studies of MUM performance.

In summary, WAnT is a potential independent predictor of MUM performance based the following criteria: 1) The WAnT is a valid measurement of anaerobic capacity as supported by both invasive and non-invasive studies of the anaerobic contributions during this test, 2) the test has high reliability, 3) the WAnT has been previously and successfully correlated to running performance of various distances. On this basis, WAnT is a promising candidate for application in this study.

#### **1.3.4. Summary of Candidate Variables for Prediction of MUM Performance**

As outlined in sections 1.1. – 1.3. there are several physiological variables which may determine MUM performance. Firstly, there is the aerobically based variable of critical velocity, which is thought combine the three main elements of Coyle's model of endurance performance ability which are  $\dot{V}O_{2MAX}$ , % of  $\dot{V}O_{2MAX}$  at the lactate threshold, and RE (Coyle 1995). Secondly, there are velocity-time Models and Wingate anaerobic testing estimates of anaerobic capacity. These tests can be used to comprehensively assess if MUM performance depends on AC and this will help to give insight into the relative importance of both aerobic and anaerobic independent variables in MUM performance.

### **1.4. Anthropometric Predictors of Endurance Performance**

Besides physiological variables, anthropometric characteristics can also be used to determine endurance performance. In ultra-endurance sports such as cycling, skating and iron-distance events this determination has been successfully made (Hoffman 2008, Knechtle 2014, Barandun et al. 2012), however, there has been little study of

anthropometric variables such as surface-area-to-body-mass ratio, lower-limb girths, and somatotypes as determinants of in MUM performance. The description and rationale for inclusion of each of these anthropometric variables are detailed in the following sections.

#### **1.4.1. Impact of Anthropometric Variables on Thermoregulation and Endurance Performance**

##### ***Body Mass and Surface-area-to-body-mass Ratio***

A lower body mass and a greater surface-area-to-body-mass ratio ( $A_{DM}^{-1}$ ) has been shown to be predictive of a lower heat gain during exercise in hot, humid conditions (Marino et al. 2000). Endurance male runners with various body masses were tested during exercise at ambient dry-bulb temperatures of 15, 25, 35°C (Marino et al. 2000). The runner's mass and running speed were used to calculate the rate of heat transfer from metabolism, while calculations using skin, ambient, and rectal temperature, as well as body surface area was used to determine the rate of heat loss from both convection and radiation, as well as overall rate of heat storage (Marino et al. 2000). They showed body mass was positively correlated with the rate of heat gain in 25 and 35°C temperatures (Marino et al. 2000). On this basis, Marino concluded with respect to thermal balance that lighter versus heavier runners have an advantage in hot, humid events since they gain less heat (Marino et al. 2000). As a result, they have lower core temperatures, which is associated with increased performance (Nybo et al. 2001). As described below, the mass of an athlete might be even more relevant to thermoregulation when surface area is also measured to give surface-area-to-body-mass ratio.

Marino et al. (2000) also found that  $A_{DM}^{-1}$  had a significant negative relationship to the rate of heat storage during the 25 and 35°C condition, with participants having a greater  $A_{DM}^{-1}$  also having a lower the rate of heat storage (Marino et al. 2000). A study involving a stepping test for 180 min at 40°C in 40% relative humidity also found that a greater  $A_{DM}^{-1}$  predicted a lower the rate of heat storage and rectal temperature increase (Epstein, Shapiro, and Brill 1983). As suggested by Marino et al. (2000), this relationship is likely because a greater surface area relative to body mass means a greater potential for evaporative heat loss relative to the rate of heat gain from

metabolism (Marino et al. 2000). In this way, a greater  $A_{DM}^{-1}$  can facilitate a higher rate of heat loss from the surface of the body and help maintain a lower core temperature. Therefore,  $A_{DM}^{-1}$  may influence MUM performance through the mechanism of a reduced propensity for hyperthermia. As well, a similar metric of area for surface heat exchange for a given mass is surface area to mass adjusted for the covariate of body mass. A description of the effects of hyperthermia in relation to MUM performance and fatigue is given below.

### ***Hyperthermia and Athletic Performance***

Since select anthropometric characteristics might influence heat loss during exercise, it is relevant to describe the potential effect of hyperthermia on MUM performance. Hyperthermia's effect on  $\dot{V}O_{2\text{ MAX}}$  and performance time has been evaluated in endurance-trained males (Nybo et al. 2001). The conditions used included hydrated and dehydrated individuals who were either normothermic or hyperthermic. Dehydration was defined as a 4% loss of body weight and achieved by a 2-h exercise trial in 37°C at 50%  $\dot{V}O_{2\text{ MAX}}$ , while hyperthermia was defined as an esophageal temperature 1°C above normal resting values and a skin temperature ~7°C higher (Nybo et al. 2001). The results indicated that during hyperthermic dehydrated and hyperthermic euhydrated conditions individuals had a significantly lower  $\dot{V}O_{2\text{ MAX}}$  and lower oxygen pulse pressure relative to their normothermic euhydrated trials, as well as a higher heart rate in hyperthermic trials relative to normothermic trials regardless of hydration state (Nybo et al. 2001). The authors concluded that a combination of elevated skin and core temperatures have the potential to inhibit athletic performance. A possible mechanism for this effect might be a reduction in stroke volume, which has been observed to progressively decrease as core temperature rises (González-Alonso et al. 1999). Gonzalez-Alonso et al. (1999) showed this change in stroke volume in an experiment of seven endurance-trained males exercising in a 40°C, 19% RH environment (González-Alonso et al. 1999). In this experiment, participants underwent pre-heated, control or pre-cooled treatments prior to starting exercise (González-Alonso et al. 1999). Stroke volume was found to decline with a greater level of hyperthermia, with a higher core temperature showing a progressively lower stroke volume and cardiac output despite an increase in heart rate (González-Alonso et al. 1999).

Hyperthermia's inhibition of athletic performance is not limited to a lowering of  $\dot{V}O_{2MAX}$  and stroke volume. Hyperthermia induces changes to enzymatic reactions (Kent 2006, Asmussen and Boje 1945) as well as changes to central fatigue (Nybo and Nielsen 2001, Nybo 2008) and fuel utilization (Fernández-Elías et al. 2015, Fink, Costill, and Van Handel 1975). Enzymatic reactions are effected by the  $Q_{10}$  effect which increases the rate of metabolic pathways within the muscle as temperature rises (Kent 2006, Asmussen and Boje 1945). During short-term anaerobic events, hyperthermia can improve performance (Sargeant 1987). Despite this improvement in short-term events, exercise hyperthermia in endurance events is suggested to inhibit, or not improve performance, as evident for shorter duration exercise sessions (Nybo 2008). This inhibition is possibly due to a variety of mechanisms. Firstly, as compared to the cold, there is an increased rate of glycolysis during hyperthermia and therefore an increased rate of glycogen use giving an earlier glycogen depletion (Fink, Costill, and Van Handel 1975). A study of male participants in 41°C and 15% RH versus 9°C and 55% RH exercising in three 15-min high intensity trials found that in the hyperthermic conditions glycogen breakdown was 1.8 times greater than in the cold conditions (Fink, Costill, and Van Handel 1975). This increase could lead to glycogen depletion at an earlier time in MUMs.

Another explanation for hyperthermia's role in inhibiting endurance performance could be central fatigue (Nybo and Nielsen 2001). Nybo and Nielsen (2001) observed evidence for this effect in a group of trained cyclists who cycled for 1 hr in either normothermic (18°C) or hyperthermic (40°C) conditions. They found voluntary muscle activation percentage to be ~28% lower at the end of sustained maximal voluntary isometric contraction in the hyperthermic versus the normothermic condition (Nybo and Nielsen 2001). Based on the detrimental effects of hyperthermia listed above, it seems reasonable to suggest that hyperthermia would place MUM runners at a disadvantage during the race. Therefore, anthropometric characteristics, such as a larger surface area for a given mass, which would help to delay the onset or minimize the severity of hyperthermia, would be advantageous to runners during a MUM race.

Actively-induced hyperthermia in MUM athletes might be especially relevant for several reasons. This relevancy is because in some MUM events a lack of tree cover

can present a high exposure to radiant heat stress while in other conditions tree cover may be high. This increased tree cover would reduce radiant heat exposure but may give high relative humidity due to the micro-environment created within a forest (Stoutjesdijk and Barkman 2014) as well as due to a possible decrease in wind exposure (Peng et al. 2014). As described above, a higher  $A_{DM}^{-1}$  or  $A_D$  adjusted for the covariate of body mass, may help to mitigate both rises and skin and internal temperature by providing more surface area relative to mass for heat loss in MUM runners.

#### **1.4.2. The Effect of Anthropometric Variables on Anaerobic Capacity**

Anthropometric variables may also play a role in determining anaerobic capacity. A larger limb cross-sectional area (CSA) has been linked to a greater anaerobic capacity through the mechanism of greater stores of ATP and PCr (Miura et al. 2002). Greater lower-limb CSA will also allow for more storage of muscle glycogen (Fairchild et al. 2002). Muscle glycogen concentration is normally  $\sim 110 \text{ mmol}\cdot\text{kg}^{-1}$  wet weight of muscle but can increase to  $200 \text{ mmol}\cdot\text{kg}^{-1}$  with carbohydrate loading (Fairchild et al. 2002). Therefore, compared to smaller lower-limb CSA, larger limb CSA will also allow for a greater store of glycogen to be metabolised during a MUM race. These potential advantages, however, should be considered within the context of possible disadvantages of a greater overall body mass that gives an added load to a MUM runner.

Despite the possible advantages described above, a relationship between CSA and finishing time should not be presumed to be linear due to the increase in overall body mass which must accompany an increased CSA. Therefore, eventually, the advantages of increased ATP, PCr and glycogen stores could possibly be negated by the increased energetic demand for moving the additional body mass. Accordingly, studies of marathon runners that report a positive relationship between lower calf girth and race time should be viewed with caution unless they have made some attempt to account for the size dependency of CSA and also taking into account the possible presence of high leverage points in the data (Schmid et al. 2012). Taking this size dependency into account is important to try and better understand the isolated effect of CSA independently from the accompanied increase in body mass. It is notable, however,

that lean body mass has been observed to have a negative relationship with 300-m sprint performance time (Perez-Gomez et al. 2008), whereby lean body mass explained 28% of the variance in 300 m sprint time. The optimal CSA and limb girths for MUM runners have yet to be determined and in such an analysis.

### **1.4.3. Somatotypes**

Somatotypes may also be an important descriptor of the ideal body type for mountain marathons. The Heath-Carter method of somatotyping is a method of categorizing the linearity, adiposity and muscularity of the human body (Carter 2002). This method employs anthropometric measurements of the body to determine the relative scores of ectomorphic, mesomorphic, and endomorphic components of the somatotype on a scale of 0 to 9 for each somatotype component (Carter 2002). Ectomorphy is regarded as a measure of linearity and a high value ectomorphy component corresponds to a body that can be described as long and thin, with a lack of muscular definition (Willgoose and Rogers 1949). A predominance of mesomorphic characteristics gives a high value mesomorphy component which is described as those with large bones and large and a well-defined musculature (Willgoose and Rogers 1949). Finally, more pronounced endomorphic characteristics described a body type with a emphasises on shorter limbs with a higher adiposity (Willgoose and Rogers 1949). The final composite somatotype score for is given with values assigned to each of the above three components.

Endurance performance in an Ironman-distance competition indicated that higher ectomorphic and lower endomorphic scores predicted overall race performance with a higher ecto-mesomorph score being correlated with a faster finishing time (Kandel, Baeyens, and Clarys 2014). In this study, the somatotype accounted for 30.4% of iron-distance running performance, with split time decreasing with a lower endomorphy and a higher ectomorphy (Kandel, Baeyens, and Clarys 2014). Elite Kenyan marathon athletes have also shown a more pronounced pattern, with a high mean ectomorphy score and a mean endomorphy score that was more than 50% lower (Vernillo et al. 2013). There are two mechanisms thought to underlie why a dominant ectomorphic somatotype gives a better endurance performance. Firstly, it has been suggested that the slim stature of a

runner with a predominant ectomorphic somatotype may improve running economy (Vernillo et al. 2013) as lower relative body mass to height is thought to reduce the energy cost of running (Cureton and Sparling 1980). However, it must be considered that an increased volume of training might influence both success in endurance events and predispose athletes to a more ectomorphic body type (Legaz and Eston 2005).

Secondly, some have argued that those with a meso-ecto body type respond better to endurance training relative to other body types by allowing for better physiological improvements and therefore performance outcome measures (Chaouachi et al. 2005). This advantage was shown in a study of 41 untrained, college-aged students which took part in a 12-week interval running training sessions (Chaouachi et al. 2005). The results showed that the meso-ecto group had the greatest increase in both  $\dot{V}O_{2MAX}$ ,  $\dot{V}O_2$  at OBLA and velocity at  $\dot{V}O_{2MAX}$  as compared to the endo-meso and ectomorphic groups (Chaouachi et al. 2005). As discussed in sections 1.1.1. and 1.1.2. these adaptations have been suggested to be advantageous in a MUM race as they have been shown to be predictive of endurance performance (Tanaka and Matsuura 1984, Lazzer et al. 2012). In summary, these studies suggest that those with a dominant ectomorphic or meso-ecto body type stand to have a high running economy and improved aerobic adaptations to training. It follows that somatotypes are a viable independent variable to be assessed in the prediction of a MUM performance.

## **1.5. Central Fatigue and Psychological Factors**

Although not a main focus of this thesis it is also important to mention the possible roles of both central fatigue and psychological factors in MUM performance. Central fatigue can be described as the failure of the central nervous system to fully activate motor neurons (Nybo and Nielsen 2001, Nybo 2008) and is mentioned in section 1.4.1. as one of the possible mechanisms for hyperthermia's inhibition of endurance performance (Nybo and Nielsen 2001, Nybo 2008). This occurrence of central fatigue is supported by reductions in both maximal voluntary contractions post marathon (Ross et al. 2007) and during hyperthermia (Nybo and Nielsen 2001). It has also been suggested, in the Central Governor model, that subconscious neural control of an athletes chosen race pace may be set by the knowledge of the duration of an event in

order to avoid a complete and dangerous loss of homeostasis (Noakes 2007). Several psychological factors have also been documented to be relevant in endurance performance (Wallace et al. 2017, McCormick, Meijen, and Marcora 2015). For example, in the heat athletes are able to exercise for longer by using motivational self-talk strategies as compared to controls (Wallace et al. 2017). Therefore, although the above factors are beyond the focus of this thesis they should never-the-less be noted as possible additional factors for determining MUM performance and could possibly be the focus of future studies on this topic.

## 1.6. Rationale

Although previous predictions of marathon and ultra marathon performance have been based on aerobic variables (Lazzer et al. 2012, Gatterer et al. 2013), other observations suggest that prolonged multi hour and multi day ultra-endurance events may be performed at higher intensities (Gatterer et al. 2013, Wirnitzer and Kornexl 2008) where anaerobic capacity may be an important determinant of performance. Furthermore, CV has been previously shown (Lazzer et al. 2012) to predict marathon performance but has yet to be studied as a predictor of MUM performance. Athletes with a higher CV are suggested to be able to maintain a higher average pace over the course of a MUM race and therefore have a faster finishing time.

Since MUMs can expose athletes to high heat stress during the race, an anthropometry and somatotype which allows for better thermoregulation is suggested to influence MUM performance. A high  $A_{DM}^{-1}$  has been shown to improve thermoregulation during exercise (Marino et al. 2000, Epstein, Shapiro, and Brill 1983) and will help runners to reduce hyperthermia-based impairment of their  $\dot{V}O_{2MAX}$  (Nybo et al. 2001) and the associated accelerated depletion of muscle glycogen (Fink, Costill, and Van Handel 1975), both of which may inhibit MUM performance.

Although it is known that excess mass can inhibit running performance (Cureton and Sparling 1980), it has also been shown that increased lower-limb lean mass has been associated with higher anaerobic capacity (Miura et al. 2002) as well as better sprinting performance (Perez-Gomez et al. 2008). Furthermore, it has been suggested

that a greater mass overall relative to runners in shorter duration endurance events might be required in these ultra-endurance events in which carbohydrate depletion is a relevant concern (Sherman et al. 1983, Hoffman 2008). With these considerations in mind, although it is recognized that eventually the energetic cost of a very large lower-limb CSA would be disadvantageous, it appears reasonable that for this population a greater lower-limb CSA, after accounting for variations on body size between runners, is suggested to provide a greater starting D' and help maintain D' on account of relatively greater muscle glycogen storage (Fairchild et al. 2002) and consequently better MUM performance.

Finally, studies relating somatotypes to performance have shown a common pattern a lower endomorphic score being related to faster performance (Kandel, Baeyens, and Clarys 2014, Vernillo et al. 2013). Endomorphy is a measure of adiposity and when relating body fat percentage to performance independently there also appears to be a relatively consistent relationship to endurance performance (Knechtle 2014). The central rationale for these relationships being that those with greater excess mass, such as body fat, would have a greater metabolic cost of movement (Cureton and Sparling 1980). Therefore, runners with the lowest value for either of these variables of endomorphy or body fat percentage should be at an advantage during and MUM.

## **1.7. Hypotheses**

With regards to physiological and performance variables, it was hypothesized for MUM runners with high aerobic power that:

- I. Critical velocity would significantly predict MUM performance, as well as performance during selected uphill portions of the race. In this case, those with a higher CV would have a faster finishing time.
- II. Those with higher measures of anaerobic capacity, as measured by D' and WAnT power, would have faster overall finishing time, as well as faster times during the uphill portions of the race.

With regards to anthropometric variables, it is hypothesized that:

- I. A greater lower-limb girth would be associated with a faster finishing time, as well as faster times during the uphill portions of the race.
- II. Surface-area-to-body-mass ratio would be negatively associated with finishing time.
- III. A lower endomorphy would be associated with a faster finishing time, as well as faster times during the uphill portions of the race.
- IV. A lower body fat percentage would be associated with a faster finishing time, as well as faster times during the uphill portions of the race.

Finally, it was hypothesized for these MUM runners that through multiple linear regression of physiological and anthropometric variables that a combination of these measures would significantly add to the explanation of variance in finishing time and hill climb times compared to the same assessment with physiological variables in isolation and anthropometric variables in isolation.

## 1.8. Chapter 1 Data

**Table 1.1** Equations for the calculation of gross efficiency

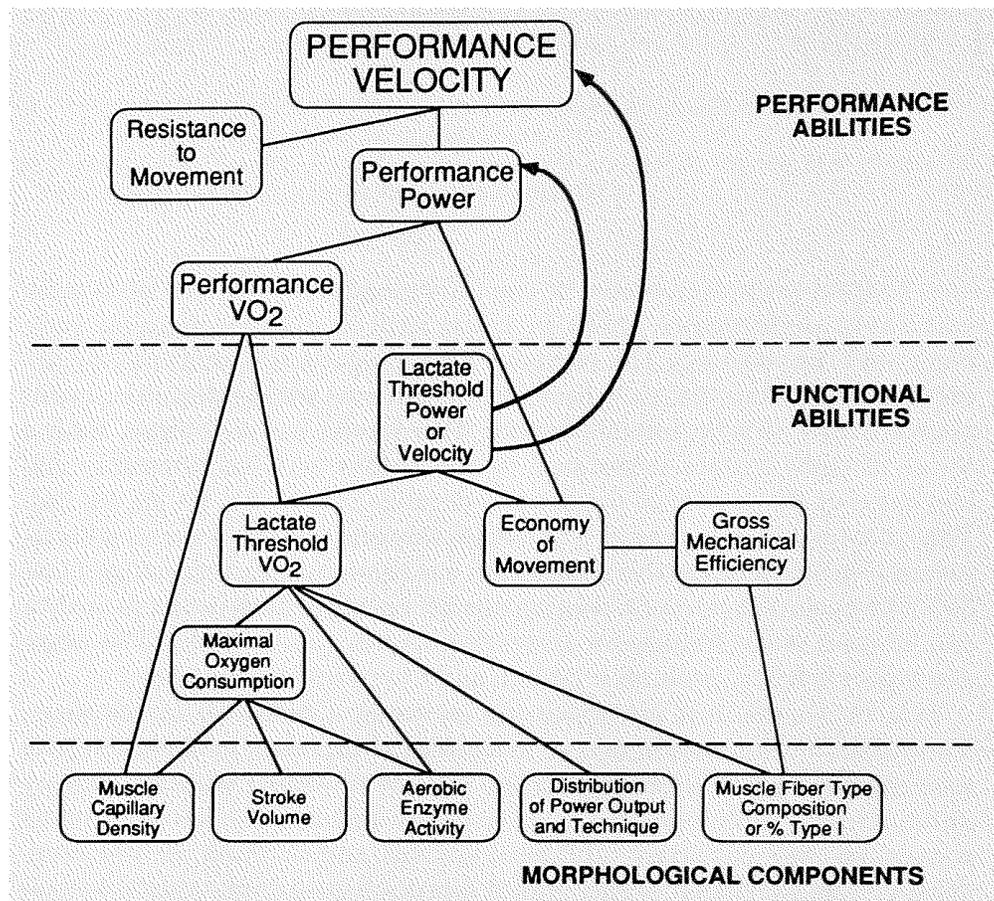
Equation Formula	Equation Number
$\text{Gross Efficiency} = \frac{\text{Mechanical Power Output}}{\text{Metabolic Power Input}}$	Equation 1.3.
$\text{Metabolic Power Input} = \dot{V}O_2 \times \text{Oxygen Equivalent}$	Equation 1.4.
$\text{Oxygen Equivalent} = 4940 \times \text{Respiratory Exchange Ratio} + 16040$	Equation 1.5.
$\text{Aerobic Power} = \text{Metabolic Power Input} \times \text{Gross Efficiency}$	Equation 1.6.
$\begin{aligned} \text{Anaerobically attributable mechanical power} \\ = \text{Mechanical PO} - (\text{Metabolic PI} \times \text{GE}) \end{aligned}$	Equation 1.7.

The units for each of the variable or constant above as are follows: Gross efficiency (unitless), mechanical power output (W), metabolic power input (W),  $\dot{V}O_2$  (L·s<sup>-1</sup>), oxygen equivalent (J·L<sup>-1</sup>), respiratory exchange ratio (unitless), aerobic power (W), anaerobically attributable mechanical power (W), mechanical power output (W), 4940 (J·L<sup>-1</sup>), 16040 (J·L<sup>-1</sup>). PO = Power output. (Noordhof et al. 2011)

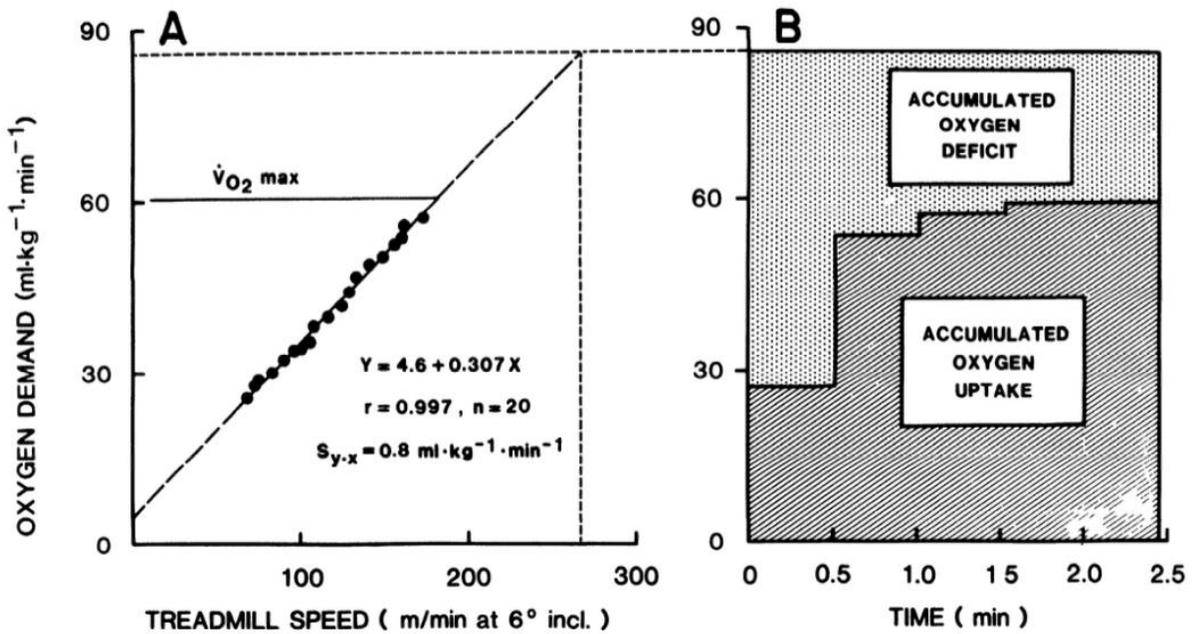
**Table 1.2** Critical power and velocity testing methods

Reference	Method	Advantages	Limitations
Burnley M, et al. 2006.	<ul style="list-style-type: none"> <li>3-min all-out cycling test (Burnley, Doust, and Vanhatalo 2006).</li> </ul> <p>Participants exercise for 3-min at maximal cadence at a power output 50% between their <math>\dot{V}O_2</math>max and ventilatory threshold as determined during maximal graded exercise testing. The last 30s of testing during this effort is deemed the end test power and the <math>W'</math> is estimated as the "power-output time integral above the end test power" (Burnley, Doust, and Vanhatalo 2006).</p>	<ul style="list-style-type: none"> <li>CP: Determined by a single laboratory test.</li> <li><math>W'</math>: determined by a single laboratory test.</li> </ul>	<ul style="list-style-type: none"> <li>Participants require high motivation to complete this test.</li> <li>Cycling tests are not specific to running or mountain marathon performance.</li> </ul>
Dekerle J, et al. 2006.	<ul style="list-style-type: none"> <li>90s all-out testing (Dekerle et al. 2006)</li> <li>Participants performed an constant cadence sprint for 90s. The power output above CP was denoted as <math>W_{90s}'</math>.</li> </ul>	<ul style="list-style-type: none"> <li>CP: Determination by a single laboratory test.</li> <li><math>W'</math>: Determination of <math>W_{90s}'</math> by a single laboratory test.</li> <li>More suitable for amateur athletes which have lower motivation during exercise testing.</li> </ul>	<ul style="list-style-type: none"> <li><math>W_{90s}'</math> and <math>W'</math> showed high disagreement</li> <li>Cycling tests are not specific to running or mountain marathon performance.</li> </ul>
Galbraith A, et al. 2014	<ul style="list-style-type: none"> <li>Single Visit Field Test (Galbraith et al. 2014)</li> <li>3600, 2400, and 1200 m running trials performed on the same day. Between each trial 30 min of recovery was given. The linear distance-duration equation was used to determine CV and <math>D'</math> based on these three trials.</li> </ul>	<ul style="list-style-type: none"> <li>Specific to weight bearing, running exercise</li> <li>CV: Able to get from a single laboratory visit</li> <li><math>D'</math>: Able to get from a single laboratory visit</li> <li>Coefficient of variation (CoV) of 0.4% for CV</li> </ul>	<ul style="list-style-type: none"> <li>The athlete needs to pace properly to maintain the maximal constant velocity possible for the given distance.</li> <li><math>D'</math> was found to have a higher CoV than CV of 13%.</li> </ul>

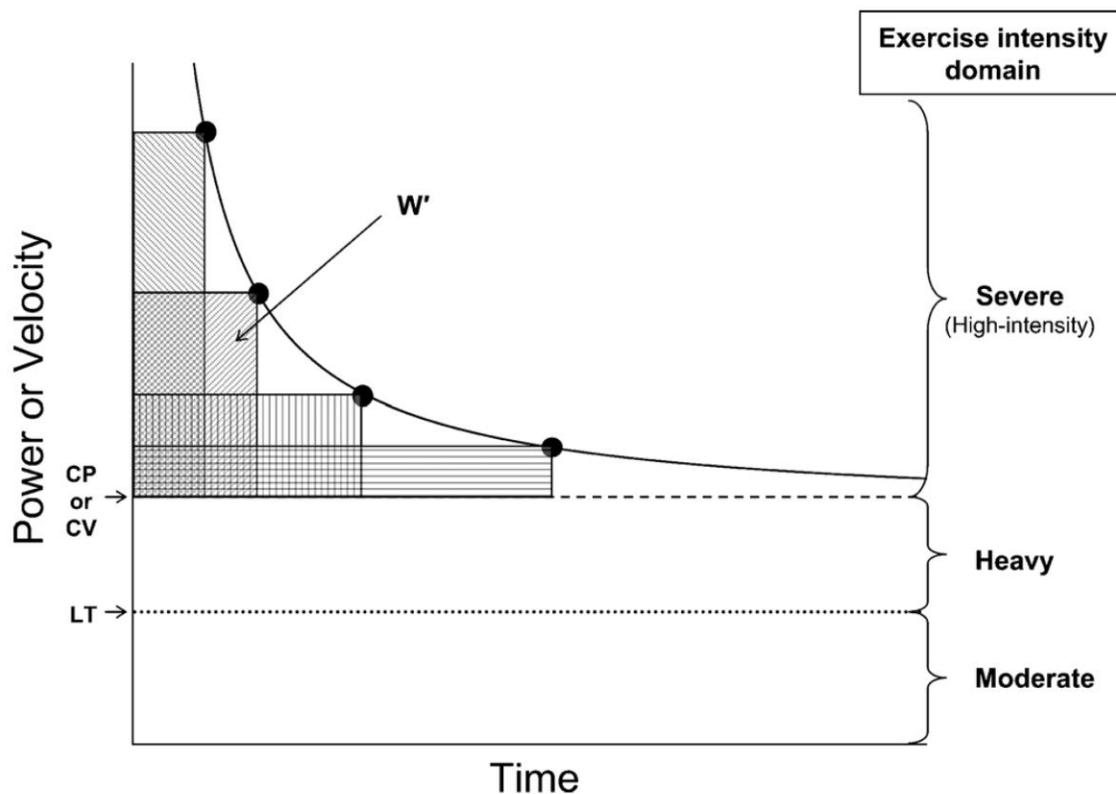
Reference	Method	Advantages	Limitations
Kranenburg KJ, and Smith DJ. 1996.	<ul style="list-style-type: none"> <li>• Time to Exhaustion Treadmill Testing (Kranenburg and Smith 1996)</li> <li>• Runners completed three time to exhaustion treadmill tests of around 3, 7 and 13 min in duration. The first and second test trial was separated by 1 hr of rest, while the final run was conducted on a second day.</li> </ul>	<ul style="list-style-type: none"> <li>• Specific to weight bearing, running exercise.</li> <li>• Athlete pacing is not an issue.</li> </ul>	<ul style="list-style-type: none"> <li>• A minimum of three testing days as a separate day of <math>\dot{V}O_2</math>max testing is also required to select running speeds for CV testing.</li> <li>• This protocol was found to over-predict 10km race performance.</li> </ul>



**Figure 1.1** Coyle's model of endurance performance ability (Coyle 1995). Used with permission from Coyle (1995), Integration of the Physiological Factors Determining Endurance Performance Ability, Figure 2.1. Hypothetical model of the interrelationships of physiological factors determining endurance performance ability. *Exercise and Sport Sciences Reviews*. Volume 23, issue 1. <https://journals.lww.com/acsm-essr/pages/default.aspx>. Page 26.



**Figure 1.2** Estimation of anaerobic metabolism using the maximal accumulated oxygen deficit method. The left panel shows the relationship between oxygen demand and treadmill speed. The right panel shows how accumulated oxygen deficit can be calculated when both the total oxygen demand and the accumulated oxygen uptake are known (Medbø et al. 1988). Reprinted from Medbo et al. (1998), Anaerobic capacity determined by maximal accumulated  $O_2$  deficit, Figure 1. Principles for determining  $O_2$  deficit. This work is protected under copyright, permission is not required for reproduction here.



**Figure 1.3** Power – Time or Velocity – Time relationship as described by the parameters of  $D'$  (m) or Anaerobic Work Capacity ( $W'$ , J) and Critical Velocity (CV,  $m \cdot s^{-1}$ ) or Critical Power (CP, W). The division between moderate and heavy work is denoted here as the Lactate Threshold (LT) (Jones et al. 2010). Jones, Vanhatalo and Burnley (2010), Critical Power: Implications for Determination of  $VO_{2max}$  and Exercise Tolerance, Figure 2: Schematic of the power–time (P–t) relationship for high-intensity exercise illustrating the location of the LT (synonymous with the GET) relative to CP for healthy, physically active young men. *Medicine and Science in Sports and Exercise*. Volume 42, Issue 10. <https://journals.lww.com/acsm-msse/pages/default.aspx>. Page 1878. Used with permission.

## Chapter 2.

# Prediction of mountain ultra marathon performance with physiological variables

## 2.1. Introduction

Mountain ultra marathon (MUM) races are events which have longer distances, steeper grades, and more variable terrain than most road races (Salah, Verla, and Tonga 2012). Determinants of mountain ultra marathon (MUM) race performance remains to be fully established. Running endurance performance has been described as the product of  $\dot{V}O_{2MAX}$ , %  $\dot{V}O_{2MAX}$  at the lactate threshold, and running economy (Coyle 1995). Whereas some studies of mountain running (Burtscher, Förster, and Burtscher 2008) and ultra trail running (Lazzer et al. 2012) indicate performance is dependent upon the above factors, other results have found no relationship between laboratory measured variables of cardiorespiratory fitness and MUM type events (Gatterer et al. 2013). Therefore, determination of MUM performance may be better resolved by expanding the investigation of MUM performance to anaerobic variables that may be important due to the steep grades within MUM courses that demand transient high-intensity efforts (Minetti et al. 2002, Staab, Agnew, and Siconolfi 1992).

The rationale was that MUM runners who have a high aerobic capacity who have also with a high anaerobic work capacity and power would have a performance advantage, especially during steep uphill sections of a MUM race that require a higher metabolic demand per unit distance compared to flat or downhill terrain (Minetti et al. 2002, Staab, Agnew, and Siconolfi 1992). At these intensities, the energetic flux through anaerobic pathways would be high (Robergs, Ghiasvand, and Parker 2004, Chidnok et al. 2013) and will cause fatigue-inducing metabolites to accumulate, especially in MUM runners without high intensity training (Chidnok et al. 2013). Accordingly, this study was

conducted to assess the determination of MUM performance with estimates of anaerobic capacity and power while controlling for the high aerobic work capacity in MUM runners.

Numerous methods exist for estimating anaerobic work capacity. These methods include invasive methods, such as muscle biopsies (Withers et al. 1991), and non-invasive methods such as maximal accumulated oxygen debt (Noordhof et al. 2011), the gross efficiency method (Noordhof et al. 2011), and velocity-time curves (Jones et al. 2010). Of these three indirect methods, velocity-duration curves were chosen for several reasons. Firstly, the anaerobic estimate of  $D'$  has been previously applied in the determination of 5000 m track running (Nimmerichter et al. 2017), which suggests this test may be applicable beyond short-term sprinting performance. Secondly,  $D'$  is determined in the modality running and is an estimated translation of anaerobic work capacity into horizontal running distance (Nimmerichter et al. 2017). Finally, this method is not only an index of anaerobic work capacity but it also gives also critical velocity (CV) which is argued to be the maximal aerobic velocity which can be sustained for prolonged periods, such as in a MUM race (Jones et al. 2010, Hill and Ferguson 1999). In addition to  $D'$ , anaerobic power was also estimated using the Wingate anaerobic test (WAnT). The WAnT is a test which has been shown to be a valid measure of anaerobic work capacity (Beneke et al. 2002), have high reliability (Jaafar et al. 2014), and has been previously correlated to 30, 300 and 800 m running performance (Perez-Gomez et al. 2008, Yoshida et al. 1990). Together these two testing methods not only helped determine if anaerobic work capacity is a determinant of MUM performance but also expanded the investigation of MUM performance with an additional aerobic performance metric with the parameter of CV.

The current study hypothesized that for MUM runners who have a high aerobic capacity that critical velocity would significantly predict MUM performance, as well as performance during selected uphill portions of the race. In this case, those with a higher CV would have a faster finishing time. This study also hypothesized that those with higher measures of anaerobic capacity, as measured by  $D'$  and WAnT power, would have faster overall finishing time, as well as faster times during the uphill portions of the race.

## **2.2. Methods**

### **2.2.1. Participants**

Thirty-four healthy participants, 7 females and 27 males, were recruited to participate in this study. Of these 34, 13 volunteers participated in the CV testing subset of this experiment. A power calculation analysis was conducted for each main outcome variable's correlation to finishing time (Table 2.1). Estimated correlations of outcome variables to race finishing time were made with either pilot data or existing studies relating these variables to endurance running performance. These main outcome variables were CV,  $D'$ ,  $\dot{V}O_{2MAX}$ , WAnT peak power (WAnT PP), WAnT mean power (WAnT MP). All independent variables are listed in the statistical analysis section 2.2.4. An alpha of 0.05 and a power of 80% was used, and 13 participants were determined to be required to show a prediction of finishing time for CV testing and 16 participants for WAnT testing variables.

Each participant received an orientation of the laboratory and a 24-h reflection period, after which each participant was required to complete a Physical Activity Readiness Questionnaire (PAR-Q) and a signed informed consent form. The SFU Office of Research Ethics approved this study.

### **2.2.2. Instrumentation**

During all laboratory tests and the mountain ultra marathon, each participant wore athletic clothing including running shoes, shorts, and a t-shirt. Each volunteer's anaerobic capacity was estimated using a Wingate test on an electronically-braked, seated cycle ergometer (LODE, Excaliber Sport, Sweden). Critical velocity testing was conducted on a 400-m track and timed using an electronic stopwatch, the weather conditions of these tests were at a temperature of 20.6 (7.4) °C and relative humidity (RH) of 49.6 (20.8) %. The CV testing was completed at an elevation of ~330 m as compared to the race elevation which varied from sea level to ~1200 m.

Aerobic power tests were performed on a treadmill (CS8.0, True Commercial Series, MO). Gas exchange was measured using a calibrated breath-by-breath

metabolic cart (Model Vmax 229d, SensorMedics, Yorba Linda, CA). Metabolic cart calibrations were performed with known gas concentrations of 26% oxygen in balanced nitrogen, and 16% oxygen, 4% carbon dioxide and balanced nitrogen. A nose clip was worn by each participant as they breathed through a two-way flow sensor. Heart rate (HR, beats•min<sup>-1</sup>) was measured and recorded using a telemetry-based wrist computer (Polar, V800, Finland). A spring-loaded lancet (OneTouch Ultrasmart and Ultra-Fine 30 Gauge Lancets, BD, NJ) and a hand-held lactate reader was used to obtain blood samples and determine blood lactate concentrations (Accutrend Lactate, Roche, Mannheim).

### **2.2.3. Protocol**

#### ***Critical Velocity Testing***

Participants completed three runs of 3,600 m, 2,400 m, and 1,200 m in a random order on a 400-m track (Galbraith et al. 2011) to establish their critical velocity and D'. Each athlete completed a warm-up consisting of 5 min of self-paced jogging and their normal stretching routine as well as 30 min of recovery between the 3 trials (Galbraith et al. 2011). This protocol included 5 min of active walking recovery and 25 min of passive recovery between trials (Karsten et al. 2016). The instruction for pacing during the run was to complete each trial with the "fastest time possible" (Galbraith et al. 2011). Lap times were announced to the participant as they crossed the start line on every lap.

#### ***Anaerobic Capacity Testing***

After a 5-min resting period, the participant performed 30-s at 40 W during which he or she was encouraged to increase their cadence to ~100 revolutions per minute. This was followed immediately by a supra-maximal, all-out 30-s Wingate test during which the volunteer was verbally encouraged to pedal as hard and as fast as possible. Anaerobic capacity testing was performed about 1-2 weeks prior to the participants completing the MUM event.

#### ***Aerobic Power Testing***

After the participant was instrumented for measurement of cardiorespiratory variables, they completed a modified Bruce maximal exercise treadmill protocol with 30-

s step duration stages and a starting incline of 6% and velocity of 4.5 km•h<sup>-1</sup>. Confirmation of a maximal effort was made by the participant meeting at least two of the following criteria: volitional exhaustion, a plateau in  $\dot{V}O_2$ , respiratory exchange ratio (RER)>1.15 and heart rate (HR) reaching an age-predicted maximum. Blood lactate was measured every 2 min of the test from the finger.

The first lactate threshold (LT1) was detected with the log lactate (LL) method as the inflection point of  $\dot{V}O_2$  versus  $\text{Log}_{10}$ [Lactate concentration] as previously described (Beaver, Wasserman, and Whipp 1985). The gas exchange threshold was detected by the inflection point of  $VCO_2$  versus  $\dot{V}O_2$  using the V-slope method as previously described (Binder et al. 2008). Within chapters 2 – 4 the gas exchange threshold will be denoted as  $\dot{V}O_{2VSLOPE}$  and the LT1 will be as  $\dot{V}O_{2LL}$  (Beaver, Wasserman, and Whipp 1985). The stage that either  $\dot{V}O_{2VSLOPE}$  or  $\dot{V}O_{2LL}$  occurred during treadmill testing was defined as the product of treadmill velocity and grade as is denoted in this chapter as Stage  $\dot{V}O_{2VSLOPE}$  or  $\dot{V}O_{2LL}$ . For example, if the participant reached  $\dot{V}O_{2VSLOPE}$  at 6 km•h<sup>-1</sup> and 10% grade the Stage value would be 6 km•h<sup>-1</sup> × 10% to give 60 km•h<sup>-1</sup>•%.

### ***Mountain Ultra Marathon Course and Conditions***

Each volunteer was a participant in either the 2014, 2015 or 2016 Knee Knacking North Shore Trail Run (KKNSTR) race. This race was founded in 1989 and has rapidly grown from 8 to ~262 participants per year. The course contains a cumulative ~ 2400 meters of ascent and a cumulative ~ 2500 meters of descent. The course terrain is highly variable with steep, unstable surfaces, rocks, roots and other obstacles to navigate. In 2014, the weather was warm and sunny with dry bulb temperatures (DBT) ranging from ~17-35°C and relative humidity (RH) of ~55%. In 2015, the weather was overcast with DBT remaining at ~10-12°C and an RH of ~90%. In 2016, there was heavy rainfall with DBT of ~14-20°C and ~100% RH. All athletes had access to 11 aid stations along the course.

The course was approximately 45 km included three main ascents (Fig. 2.1). The first and the largest ascent is Black Mountain (hill 1) with a climb of approximately 1000 m. The second major ascent starts just prior to Cleveland Dam and the aid station at the course halfway point and Grouse Mountain (hill 2), has an elevation change of

approximately 300 m. Since the start of this climb is just prior to an aid station, climb times were taken from the point of depart after to the aid station to the maximal elevation on Grouse Mtn. The last major ascent of 300 m was on Seymour Mountain (hill 3). Hill climb times were determined from Polar V800 data and defined as the elapsed time each participant spent on these 3 longest uphill sections of the course. Hill 1 was ~8 km in length from the start line, hill 2 was ~ 3 km in length and towards the middle of the race, and hill 3, the final main ascent before the end of the race, was ~3 km in length.

#### **2.2.4. Statistical Analysis**

All statistical analyses were performed using IBM SPSS Statistics software (Version 24, Armonk, NY, USA). Pearson product moment correlations, univariate linear regression analysis, as well as multiple univariate stepwise linear regression analysis were employed to assess the relationship between either finishing time or any individual hill climb times with 14 independent variables. The first 9 of these variables included CV, D',  $\dot{V}O_{2MAX}$ , WAnT PP, WAnT MP,  $\dot{V}O_{2VSLOPE}$ ,  $\dot{V}O_{2LL}$ , Stage  $\dot{V}O_{2VSLOPE}$ , and Stage  $\dot{V}O_{2LL}$ . An additional 5 variables,  $\dot{V}O_{2MAX}$ , WAnT PP, WAnT MP,  $\dot{V}O_{2VSLOPE}$  and  $\dot{V}O_{2LL}$ , were all mass-adjusted by regressing each against body mass and then residuals of each variable were regressed against finishing time and hill climb times. The purpose of including these residuals was to allow for an evaluation of these variables with a control for body mass (Tanner 1949, Packard, Birchard, and Boardman 2011). For each regression model, there was only one dependent outcome variable being predicted. For further details describing the statistical methodology used in this chapter, as well information on the construction of graphs, please refer to Appendix A.

Residual analysis for the goodness-of-fit was employed for first-order regressions of the dependent variables of finishing time and hill climb times. This analysis was done in two ways. Firstly, there was a visual inspection of the residuals. Secondly, a Shapiro-Wilks' (W) test was employed. The criterion of this test was a p-value of 0.05 or greater, where the null hypothesis was a normal distribution of the residuals (Ghasemi and Zahediasl 2012).

Finally, to control for the effect of aerobic power which may influence WAnT variables, a follow-up analysis using partial regression was used to correlate mass-

adjusted WAnT MP and PP versus finishing time and hill climb times while controlling for the effect of mass-adjusted  $\dot{V}O_{2MAX}$  (see Appendix A for further description).

Throughout this chapter and thesis, Pearson product moment correlation ( $r$ ) values are used to give the magnitude and direction of the relationships between dependent and independent variables. Univariate linear regression analysis and univariate stepwise linear regression analysis equations are given as coefficients of determination ( $R^2$ ) to communicate the total amount of variance in MUM performance explained by a given independent variable or by the full model.

## 2.3. Results

### 2.3.1. Laboratory and Race Outcome Measures

All participants ( $n=34$ ) completed the race, the mean finishing time over the three years was 458.3 (63.5) min (mean(SD)). The first, second, and third hills were ascended in 107.3 (12.8) min, 54.4 (11.0) min, and 42.7 (5.9) min, respectively ( $n=28$  for all three hills). One participant withdrew from the study due to knee pain and did not complete further aerobic power or critical velocity testing, and due to technical difficulties with the HR monitors six participants did not have recordings of their hill climb times.

The result of laboratory-based aerobic power testing was a  $\dot{V}O_{2MAX}$  of 4.1 (0.7)  $L \cdot \text{min}^{-1}$  and 57.8 (6.2)  $\text{mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$  ( $n=26$ ). The  $\dot{V}O_{2VSLOPE}$  was 2.8 (0.6)  $L \cdot \text{min}^{-1}$ , 40.4 (7.9)  $\text{mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$  ( $n=24$ ), and 70% of  $\dot{V}O_{2MAX}$ . The  $\dot{V}O_{2LL}$  was 3.3 (0.8)  $L \cdot \text{min}^{-1}$ , 45.9 (10.4)  $\text{mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$  ( $n=24$ ), and 80% of  $\dot{V}O_{2MAX}$ . The average treadmill velocity and grade at  $\dot{V}O_{2VSLOPE}$  was 8.3 (1.0)  $\text{km} \cdot \text{h}^{-1}$  and 7.9 (1.5) % grade ( $n=24$ ), at  $\dot{V}O_{2LL}$  it was 9.3 (0.9)  $\text{km} \cdot \text{h}^{-1}$  and 9.3 (1.6) % grade ( $n=24$ ).

Wingate anaerobic testing mean power output across the 30 s test was 531.9 (119) W ( $n=29$ ) and the peak power during the 30 s test was 916 (218) W ( $n=29$ ). Critical velocity running tests on the 400 m track resulted in a CV of 3.5 (0.4)  $\text{m} \cdot \text{s}^{-1}$  and an estimated  $D'$  of 190.17 (70.1) m ( $n=12$ ). Individual linear relationships of running velocity

versus reciprocal completion times for 1200 m, 2400 m and 3600 m (Fig. 2.2) show the determination of each CV and D' value.

### 2.3.2. Prediction of Overall Race Time

In a first-order Pearson product-moment correlation matrix (Table 2.2) significant negative associations of finishing time were observed with of the following variables: mass-adjusted  $\dot{V}O_{2MAX}$  ( $r=-0.61$ ,  $p<0.01$ ) (Fig 2.3),  $\dot{V}O_{2LL}$  Stage ( $r=-0.58$ ,  $p<0.01$ ), CV ( $r=-0.86$ ,  $p<0.01$ ) and mass-adjusted WAnT PP ( $r=-0.59$ ,  $p<0.01$ ) (Fig. 2.4, upper plot). Also, a significant positive correlation was observed between finishing time and mass-adjusted  $\dot{V}O_{2VSLOPE}$  ( $r=0.44$ ,  $p<0.05$ ). Individual plots of finishing time as a function of D' (Fig. 2.5) as well as of mass-adjusted WAnT MP (Fig 2.4, lower plot) showed that neither variable was predictive of finishing time. The association of WAnT PP and finishing time remained significant ( $r=-0.48$ ,  $p<0.05$ ) in the follow-up partial regression while controlling for mass-adjusted  $\dot{V}O_{2MAX}$ .

In multiple univariate stepwise linear regression analysis, CV was the sole predictor of finishing time ( $R^2=0.75$ ,  $p<0.001$ ); the slope of  $-129.08$  (SEE 23.84)  $\text{min}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$  was found to be significantly different from zero ( $p<0.001$ ). In a two-variable multiple regression model with both, CV and D' entered, D' did not significantly increase the explanation of variance ( $p=0.78$ ) (Fig 2.6). Homoscedasticity and a normal distribution were observed in the residuals from finishing time plotted as a function of CV as supported by the Shapiro-Wilk's analysis ( $p=0.88$ ) (Fig 2.7).

### 2.3.3. Prediction of Hill Climb Times

For hill 1 climb time, the first order Pearson product-moment correlation matrix (Table 2.3) showed negative associations for mass-adjusted  $\dot{V}O_{2MAX}$  ( $r=-0.60$ ,  $p<0.01$ ),  $\dot{V}O_{2LL}$  Stage ( $r=-0.65$ ,  $p<0.01$ ), CV ( $r=-0.86$ ,  $P<0.01$ ) and mass-adjusted WAnT PP ( $r=-0.59$ ,  $P<0.01$ ). The association of WAnT PP and hill 1 climb time remained significant ( $r=-0.54$ ,  $p<0.05$ ) in the follow-up partial regression while controlling for mass-adjusted  $\dot{V}O_{2MAX}$ .

In multiple univariate stepwise linear regression analysis CV was the sole predictor of hill 1 climb time ( $R^2=0.73$ ,  $p=0.002$ ); the slope of  $-23.56$  (SE 5.01)  $\text{min}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$  was found to be significantly different from zero ( $p=0.002$ ) (Fig 2.8). Homoscedasticity and a normal distribution were observed in the residuals from hill 1 climb time plotted as a function of CV as supported by the Shapiro-Wilk's analysis ( $p=0.60$ ) (Fig 2.9).

A first order Pearson product-moment correlation matrix (Table 2.4) showed only CV to be associated with of hill 2 climb time ( $r=-0.82$ ,  $p<0.01$ ). In univariate stepwise linear regression analysis  $\dot{V}O_{2LL}$  Stage was the sole predictor of hill 2 climb time ( $R^2=0.68$ ,  $p=0.003$ ); the slope of  $-0.27$  (SE 0.07)  $\text{min}\cdot\text{km}^{-1}\cdot\text{h}^{-1}\cdot\% \text{grade}^{-1}$  was found to be significantly different from zero ( $p=0.003$ ) (Fig 2.10). Homoscedasticity and a normal distribution were observed in the residuals from hill 2 climb time plotted as a function of  $\dot{V}O_{2LL}$  Stage as supported by the Shapiro-Wilk's analysis ( $p=0.14$ ) (Fig 2.11).

For hill 3 climb time first order Pearson product-moment correlation matrix construction (Table 2.5) showed a negative association of Mass-Adjusted  $\dot{V}O_2$  ( $r=-0.56$ ,  $p<0.01$ ), Mass-Adjusted  $\dot{V}O_{2SLOPE}$  ( $r=0.46$ ,  $p<0.05$ ),  $\dot{V}O_{2SLOPE}$  Stage ( $r=-0.47$ ,  $p<0.05$ ),  $\dot{V}O_{2LL}$  Stage ( $r=-0.61$ ,  $p<0.01$ ), CV ( $r=-0.90$ ,  $P<0.01$ ), Mass-Adjusted WAnT MP ( $r=-0.46$ ,  $P<0.05$ ) and Mass-Adjusted WAnT PP ( $r=-0.56$ ,  $P<0.01$ ). The association of WAnT PP and hill 3 climb time remained significant ( $r=-0.50$ ,  $p<0.05$ ) in the follow-up partial regression while controlling for mass-adjusted  $\dot{V}O_{2MAX}$ .

In multiple univariate stepwise linear regression analysis, both CV and  $\dot{V}O_{2LL}$  Stage were predictors of hill 3 climb time (Table 2.6). The final equation predicted 90% ( $p<0.001$ ) of hill 3 climb time (Fig 2.12):

$$\text{hill 3 climb time (min)} = -7.64 \cdot \text{CV (m}\cdot\text{s}^{-1}) + -0.13 \cdot \dot{V}O_{2LL} \text{ Stage (km}\cdot\text{h}^{-1}\cdot\% \text{grade}^{-1}) + 81.09(\text{min})\dots\dots\text{Equation 1}$$

Homoscedasticity and a normal distribution were not observed in the residuals from hill 3 climb time plotted as a function of the above equation as supported by the Shapiro-Wilk's analysis ( $p=0.02$ ) (Fig 2.13).

## 2.4. Discussion

The first main novel outcome from this study was that in addition to a significant negative mass adjusted  $\dot{V}O_2$  predicting finishing time ( $r=-0.60$ ,  $p<0.01$ ), a higher measure of anaerobic work capacity, mass-adjusted WAnT peak power, was significantly and negatively associated with finishing time ( $r=-0.59$ ,  $p<0.01$ ), as well as with climb times for hills 1 and 3. This first correlation between finishing time and mass-adjusted WAnT PP was found to remain significant after accounting for mass-adjusted  $\dot{V}O_{2MAX}$ . These results partially support the hypothesis that indices of higher anaerobic work capacity or power would predict MUM finishing time, as well as hill climb times. The second main novel outcome was using univariate stepwise linear regression analysis that 75% of the variance in mean MUM finishing time for runners was explained by their variations in critical velocity. The findings also indicate the explanation of variance of hill climb time was significantly contributed to by CV and the  $\dot{V}O_{2LL}$  Stage with a combination of these two explaining the last hill climb time. These results support the hypothesis that CV would significantly predict MUM finishing time, as well as hill climb times. No associations, however, were found between D' and any measure of performance. This may be due to a high coefficient of variation previously observed in this measurement of D' (Galbraith et al. 2011) or due to WAnT better representing uphill running as described further below.

Indices of anaerobic work capacity and power have been previously correlated with medium duration exercise performance that is about 2-3 hr in duration. Inoue et al. (2012), found significant negative correlations between both 5-time repeated WAnT PP ( $R^2 = 0.62$ ) and WAnT MP ( $R^2 = 0.40$ ) to cross-country circuit bike race time (Inoue et al. 2012). In comparison to the current study, however, a WAnT PP or WAnT MP did not correlate with performance and the race duration was much shorter than a MUM (Inoue et al. 2012). In another study, anaerobic work capacity was predictive of performance for an 8.05 km cross-country running race in which  $W'$  was estimated using the critical power model (Bulbulian, Wilcox, and Darabos 1986). In Bulbulian et al.'s study,  $W'$  was determined by cycle ergometry and was found to significantly add to the prediction of 8.05 km cross country running completion times in both a two-variable linear multiple regression model including  $W'$  and critical power, and in 3-variable linear multiple

regression model with  $\dot{V}O_{2MAX}$ , critical power and  $W'$  (Bulbulian, Wilcox, and Darabos 1986). The 3-variable model explained a total of 76% of the variance of completion time with  $W'$  being determined as a large determinant of the total explanation of variance with a 58% contribution (Bulbulian, Wilcox, and Darabos 1986). The current results expand upon these past studies by finding similar strengths of association in a MUM event which is much longer in duration, and also by providing evidence that these associations are significant even after adjusting for the effect of aerobic power.

Bicycle and running mountain multi-stage ultra marathon results indicate that exercise intensities during these events might be higher than expected. An intensity of 81% of laboratory-determined maximal HR was observed in the first 36.3 km stage of the eight-day, 305-km running ultra mountain marathon (Gatterer et al. 2013) and 84% laboratory-determined maximal HR was maintained during the first stage of an eight-day, 662-km mountain cycling ultra race (Wirnitzer and Kornexl 2008). Although the average intensity in this second study (Wirnitzer and Kornexl 2008) was below the second lactate threshold, or OBLA, there appear to be large portions of the race that is above OBLA. Specifically, during the first stage of the cycling race, ~18% of the race time was spent an estimated intensity that was above OBLA, and an additional ~18% was spent an estimated intensity that was above a blood lactate concentration of 6 mmol·L<sup>-1</sup> (Wirnitzer and Kornexl 2008). These exercise intensities suggest that the proportion of anaerobic metabolism relative to aerobic metabolism might be greater than previously thought for ultra distance sports, as even medium-distance track running of 1500 m to 3000 m has been argued to have minimal anaerobic energy contributions (Duffield, Dawson, and Goodman 2005). Indeed, during a race, surges to pass a competitor on the trail could require an increased anaerobic contribution during the race as has been argued to occur in cycling (Noordhof, Skiba, and de Koning 2013). Another possibility in MUM races is that transitioning to steep inclines may greatly increase anaerobic metabolism if the pace is not sufficiently decreased (Minetti et al. 2002, Staab, Agnew, and Siconolfi 1992). The basis for uphill climbs greatly increasing metabolic demands is well represented by Minetti et al. (2002). In this study it was shown that the cost of walking at a velocity of ~ 1 m·s<sup>-1</sup> on a 45% slope is ~ 17 J·kg<sup>-1</sup>·m<sup>-1</sup> compared to ~ 1.6 J·kg<sup>-1</sup>·m<sup>-1</sup> on the level or ~ 3.5 J·kg<sup>-1</sup>·m<sup>-1</sup> on a -45% slope (Minetti et al. 2002). This argument is supported by high concentrations of blood lactate, up to 7.2(2.3) mmol·L<sup>-1</sup>, which have been directly

observed in courses involving sections of uphill running (Staab, Agnew, and Siconolfi 1992).

In summary, based on the above evidence three main points can be made: 1) Major portions of endurance races may be run at above the OBLA. 2) Uphill walking is known to greatly increase the energy cost of movement. 3) Uphill running has been shown to significantly increase blood lactate concentration – indicating a net accumulation of lactate as the influx of lactate from the working muscle outpaces its systemic elimination (Binder et al. 2008). If the systemic elimination rate was assumed to be constant this accumulation of blood lactate could be assumed to be an index of anaerobic metabolism (Brooks and Mercier 1994). With these main points in mind, it seems reasonable to suggest that short-duration, largely anaerobic, efforts might be occurring during the MUM race. It is the presence of these anaerobic efforts which could explain why runners with higher mass-adjusted WAnT PP were associated with a faster finishing time during this race, even after accounting for the effect of aerobic power.

The rate of glycogen depletion is an important consideration in endurance events that have a large proportion of energy transfer from the aerobic energy pathway. Therefore, it might also be considered how increased anaerobic metabolism could lead to glycogen depletion during a MUM race and subsequently inhibit anaerobic capacity (Miura et al. 2000). The potential of depletion of glycogen reserves during a race is highlighted by a study of 10 well-trained male runners that glycogen loaded before participating in a 42.2 km footrace (Sherman et al. 1983). Muscle glycogen was found to decrease from  $196 \text{ mmol}\cdot\text{kg}^{-1}$  wet weight to just  $25 \text{ mmol}\cdot\text{kg}^{-1}$  wet weight (Sherman et al. 1983). In this case the participants underwent glycogen loading, but the depletion could be even more severe in cases in which glycogen loading was not undertaken. On this basis, although increased anaerobic energy metabolism would be required for high-intensity sections of a given MUM race, it seems that athletes must be cautious not to deplete their glycogen stores through these repeated high intensity efforts. Additionally, on the basis of glycogen depletion, it is important to highlight the limitation that anaerobic capacities measured in laboratory and track settings cannot be assumed to remain constant throughout the duration of a MUM (Miura et al. 2000). That is to say that anaerobic capacities measured in laboratory and track settings likely better represent an athlete's anaerobic capacity towards the start of a MUM race. Further studies might seek

to measure both D' and CV immediately following a MUM to evaluate how a MUM influences D'.

In the current study, mass-adjusted Wingate PP was found to be associated with finishing time while D' determined from running exercise was not. Although the CV testing from which D' is derived is most specific to the MUM and might be expected to be best associated with finishing time, this D' result might be explained by its large coefficient of variation, ranging from ~9-18%, as previously observed in a group of 10 male middle distance runners (Galbraith et al. 2011). It is also possible that WAnT testing might better represent the pattern of muscle activation during uphill running, which has been shown to significantly increase the activation of the vastus group of the lower-limb (Sloniger et al. 1997b); however, this better representation of uphill running by WAnT has yet to be conclusively shown.

Our current study investigated CV as well as anaerobic work capacity and power in the prediction of MUM performance. Critical velocity has been previously employed as a predictor of marathon finishing times in a mostly flat, paved course (Florence and Weir 1997). Florence et al.(1997) showed in a group of 12 runners that 76% of marathon finishing was explained by CV (Florence and Weir 1997). Our results suggest that CV contributes similarly to the explanation of variance ( $R^2=0.75$ ,  $p<0.001$ ) in MUM finishing time.

In addition to CV, the current findings expand upon the determination of MUM performance with gas exchange thresholds, with  $\dot{V}O_{2LL}$  Stage being correlated with finishing time and  $\dot{V}O_{2LL}$  Stage predicting both hill 2 and 3 climb times. Although previous results of MUM performance have not found a relationship between cardiorespiratory fitness and performance (Gatterer et al. 2013), Burtscher et al. (2008) concluded that  $\dot{V}O_2$  at the first lactate threshold is the main predictor of performance in mountain running (Burtscher, Förster, and Burtscher 2008). Our results do support the latter study as  $\dot{V}O_{2LL}$  Stage appears to be an important determinate of hill climb time. Interestingly, in only hill climb time 3 did both CV and  $\dot{V}O_{2LL}$  Stage together predict performance. Although it is not clear why this occurred, one possibility is that a combination of both CV and  $\dot{V}O_{2LL}$  Stage are more crucial in later stages of the race where moderate to severe

glycogen depletion might be present (Sherman et al. 1983) and therefore anaerobic capacity might be inhibited (Miura et al. 2000). Any conclusions or interpretations of equation 1 for predicting hill 3 climb time, however, must be made cautiously as the Shapiro-Wilk's analysis indicated that a normal distribution of the residuals was not present.

The finding of CV as a predictor of MUM performance lends insight into the physiological and biochemical basis of MUM performance. Critical velocity and critical power are thought to represent the maximal sustainable aerobic metabolic rate for a given type of exercise (Poole et al. 2016, Jones et al. 2010). This understanding of CV is supported by studies examining exercise intensities above CP in which blood lactate concentration begins to rise exponentially and the slow portion of  $\dot{V}O_2$  does not plateau (Poole et al. 1988). This intensity eventually causes the participant to reach  $\dot{V}O_{2MAX}$  and exhaustion if the competitor maintains a velocity of running that is greater than their CV (Jones et al. 2010, Hill and Ferguson 1999). Additional support for there being a critical exercise intensity as the delineation point for the accumulation of fatigue metabolites is observed from tracking metabolic responses during recovery exercise both above and below critical power as determined for single-leg knee extensions (Chidnok et al. 2013). Although caution must be taken in applying a study of short term isolated muscle contractions to a MUM, this study still provides some insight into what may be occurring within a muscle above CP. As compared to below critical power, above critical power concentrations of PCr and ATP were significantly lower, while concentrations of adenosine diphosphate, Pi and H<sup>+</sup> were all significantly greater (Chidnok et al. 2013). In other words, while recovery of key muscular metabolites was possible below critical power, above critical power this recovery did not occur and exercise could no longer be sustained (Chidnok et al. 2013). For MUM runners these observations support that those with the greatest CV would therefore also have the highest running speed prior to the accumulation of fatigue-inducing metabolites (Hill and Ferguson 1999). If velocity was lowered below CV, the runner could theoretically replenish key muscular metabolites (Chidnok et al. 2013) such as PCr and ATP (Chidnok et al. 2013) for uphill climbs which could acutely raise velocity above CV for that particular grade.

There are some potential limitations present in the current study. The first possible limitation of this study is that  $D'$  measured on flat running terrain might underestimate this value in uphill running as incline running has been shown to give a significantly higher oxygen deficit when using MAOD (Sloniger et al. 1997a). Although this effect on  $D'$  is a limiting factor, as all participants underwent the same testing protocol the underestimation of  $D'$  could be assumed to be similar and non-biased among participants. This assumption is supported by a previous study which showed a relatively consistent increase in oxygen deficit amongst its participants when comparing horizontal to incline running (Sloniger et al. 1997a). It is also possible that CV could change over the course of the race due to changes in running economy (Lazzer et al. 2012). An additional possible limitation is the use of stepwise linear regression. The use of this statistical method has been previously criticized on the basis of calculating incorrect degrees of freedom, a lack of reproducibility of results, and that the variables entered into the equation are not guaranteed to be optimal (Thompson 1995). In particular with regards to degrees of freedom, which “constrain [the] number of inquiries we may direct at our data” (Thompson 1995), statistical packages can calculate an incorrectly high number by determining degrees of freedom based only on the number of variables entered into the model (Thompson 1995). Despite these limitations, however, several steps have been taken in this chapter and thesis to attempt to minimize these issues. Firstly, wherever possible data was collected and combined with multiple years to increase the sample size which helps to minimize the issue of both degrees of freedom and lack of reproducibility of results (Thompson 1995). Secondly, it has been stated that the issues of stepwise regression are less severe when a single variable is entered into the equation as was observed in three of the four stepwise regressions in this study (Thompson 1995). Furthermore, this study has also followed the guidelines recommended by Flack and Chang (1987) that variables must be supported in the context of the current literature (Flack and Chang 1987) as is addressed in the introduction and discussion of this thesis chapter. This final point also applies to the results from the correlation results for which we have presented, for each table several significant correlations were identified and a potential for type I error does exist. That said, however, through our review of the current literature, application of partial regression analysis to better isolate the effects of independent variables and further follow up studies this chance of type I error can be mitigated.

## ***Methodological Applications for Coaches and Athletes***

Our results support the potential application of the use of Galbraith et al.'s single day, three effort, time trial to determine CV (Galbraith et al. 2011, Galbraith et al. 2014). Unlike gas exchange testing, which requires specialized equipment and professional training to conduct the test and interpret the results, CV testing can be conveniently conducted in the field using only a track and a timing device. Therefore, CV testing represents an easily accessible tool to track athletic improvement in preparation for a MUM event.

## ***Future directions***

Several recommendations can be made for future investigations of MUM performance based on the current results of this study. On the topic of anaerobic work capacity testing, it might be useful for future studies to attempt to design and validate a measure of D' testing that is performed on variable uphill terrain. This would not only give a measure of both CV and D' that is more specific to the MUM modality but also account for the level of skill and coordination which may play a roll in navigating irregular and unpredictable terrain. Another future direction could be to attempt to widen the range of D' and CV measures observed in the study population, this could be done by continuing to collect data over subsequent years of the race. This would not only theoretically increase the range of values by chance of a higher frequency of sampling, but also increase the sample size to the point where the individual effects of CV and D' could be further investigated. A combination of a more modality specific D' and a larger range of D' values within the study population would theoretically help allow for a better isolation of this variable's role in the determination of performance.

## **2.5. Conclusion**

In conclusion, our results for MUM runners with a high aerobic capacity supported the hypothesis that a greater CV would predict faster MUM finishing and hill climb times. Our results partially supported the hypothesis that anaerobic capacity would predict faster MUM finishing and hill climb times, as WAnT but not D' was correlated to MUM finishing time and two of the three hill climb times.

## 2.6. Chapter 2 Data

**Table 2.1** Power calculation based on effect sizes for outcome variables

Predictor Variable for Race finishing time	Hypothesized Effect Size (% variance explained)	Data Employed for Justification	Sample Size Required For Detection
Critical Velocity	70%	Florence et al. 1997. Found that CV explained 76% of marathon time.	8
Wingate Anaerobic Capacity Testing Variables of Peak and Mean Power	40%	2015 Knee Knacker Race, Pilot Data found >40% of the variance was explained by the Wingate Test in 2015.	17
D'	50%	Assuming approximately 10% greater contribution to finishing time as Wingate Variables from 2015 Knee Knacker Race Pilot Data.	13
Aerobic Power ( $\dot{V}O_{2MAX}$ )	70%	As much as 91% of 10 mile running time has been explained by aerobic power (Fay et al. 1989).	8

All calculations were done using G\*Power 3.1 Software using correlational bivariate normal model setting. The following input criteria are as follows: Tails = two, correlation to reject null hypothesis = hypothesized effect size, alpha error probability = 0.05, power = 0.80, correlation of null hypothesis = 0.

**Table 2.2** Pearson correlation matrix of physiological variables, CV and D' with finishing time; \*p<0.05, \*\*p<0.01.

	Finishing Time	Mass-Adjusted $\dot{V}O_2$	Mass-Adjusted $\dot{V}O_2$	$\dot{V}O_2$ VSLOPE	Mass-Adjusted $\dot{V}O_2$ VSLOPE	$\dot{V}O_2$ VSLOPE Stage	$\dot{V}O_{2LL}$	Mass-Adjusted $\dot{V}O_{2LL}$	$\dot{V}O_{2LL}$ Stage	CV	D'	Mean Power	Peak Power	Mass-Adjusted WAnT MP	Mass-Adjusted WAnT PP
Finishing Time (min), n=34	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2MAX}$ (L•min <sup>-1</sup> ), n=26	-0.26	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-
Mass-Adjusted $\dot{V}O_{2MAX}$ (L•min <sup>-1</sup> ), n=26	-0.61**	0.59**	1.00	-	-	-	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2VSLOPE}$ (L•min <sup>-1</sup> ), n=24	-0.34	0.66**	0.54**	1.00	-	-	-	-	-	-	-	-	-	-	-
Mass-Adjusted $\dot{V}O_{2VSLOPE}$ (L•min <sup>-1</sup> ), n=24	0.44*	0.35	0.59**	0.91**	1.00	-	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2VSLOPE}$ Stage (km•h <sup>-1</sup> •%), n=21	-0.25	0.09	0.18	0.63**	-0.72**	1.00	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2LL}$ (L•min <sup>-1</sup> ), n=25	-0.26	0.72**	0.57**	0.41	-0.23	-0.20	1.00	-	-	-	-	-	-	-	-
Mass-Adjusted $\dot{V}O_{2LL}$ (L•min <sup>-1</sup> ), n=25	-0.40	0.40*	0.66**	0.26	0.28	0.19	0.89**	1.00	-	-	-	-	-	-	-
$\dot{V}O_{2LL}$ Stage (km•h <sup>-1</sup> •%), n=20	-0.58**	0.21	0.65**	0.04	-0.14	-0.06	0.50*	-0.69**	1.00	-	-	-	-	-	-
CV (m•s <sup>-2</sup> ), n=12	-0.86**	0.19	0.56	0.19	-0.29	0.07	0.31	-0.47	0.71*	1.00	-	-	-	-	-
D' (m), n=12	-0.18	0.67*	0.46	0.53	-0.32	-0.15	0.63*	-0.43	-0.09	-0.26	1.00	-	-	-	-
Mean Power (W), n=29	-0.09	0.90**	0.57**	0.60**	-0.33	-0.01	0.64**	-0.33	0.13	0.27	0.63*	1.00	-	-	-
Peak Power (W), n=29	-0.21	0.87**	0.44*	0.51*	-0.20	0.17	0.61**	-0.26	0.21	0.19	0.52	0.75**	1.00	-	-
Mass-Adjusted WAnT MP (W), n=29	-0.36	0.41	0.75**	0.34	-0.40	0.00	0.34	-0.48*	0.43	0.64*	0.42	0.60**	0.16	1.00	-
Mass-Adjusted WAnT PP (W), n=29	-0.59**	0.41	0.62**	0.23	-0.23	0.31	0.38	-0.42	0.62**	0.82**	0.14	0.17	0.58**	0.28	1.00

**Table 2.3** Pearson correlation matrix of physiological variables, CV and D' with hill 1 climb time; \*p<0.05, \*\*p<0.01

	Hill 1 Climb Time	$\dot{V}O_2$	Mass- Adjusted $\dot{V}O_2$	$\dot{V}O_2$ VSLOPE	Mass- Adjusted $\dot{V}O_2$ VSLOPE	$\dot{V}O_2$ VSLOPE Stage	$\dot{V}O_{2LL}$	Mass- Adjusted $\dot{V}O_{2LL}$	$\dot{V}O_{2LL}$ Stage	CV	D'	Mean Power	Peak Power	Mass- Adjusted WAnT MP	Mass- Adjusted WAnT PP
Hill 1 Climb Time (min), n=28	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2MAX}$ (L•min <sup>-1</sup> ), n=26	-0.25	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-
Mass-Adjusted $\dot{V}O_{2MAX}$ (L•min <sup>-1</sup> ), n=26	-0.60**	0.59**	1.00	-	-	-	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2VSLOPE}$ (L•min <sup>-1</sup> ), n=24	-0.21	0.66**	0.54**	1.00	-	-	-	-	-	-	-	-	-	-	-
Mass-Adjusted $\dot{V}O_{2VSLOPE}$ (L•min <sup>-1</sup> ), n=24	-0.30	0.35	0.59**	0.91**	1.00	-	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2VSLOPE}$ Stage (km•h <sup>-1</sup> •%), n=21	-0.31	0.09	0.18	0.63**	-0.72**	1.00	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2LL}$ (L•min <sup>-1</sup> ), n=25	-0.22	0.72**	0.57**	0.41	-0.23	-0.20	1.00	-	-	-	-	-	-	-	-
Mass-Adjusted $\dot{V}O_{2LL}$ (L•min <sup>-1</sup> ), n=25	-0.32	0.40*	0.66**	0.26	-0.28	-0.18	0.89**	1.00	-	-	-	-	-	-	-
$\dot{V}O_{2LL}$ Stage (km•h <sup>-1</sup> •%), n=20	-0.65**	0.21	0.65**	0.04	-0.14	-0.06	0.49*	-0.69**	1.00	-	-	-	-	-	-
CV (m•s <sup>-2</sup> ), n=12	-0.86**	0.19	0.56	0.19	-0.29	0.07	0.31	-0.47	0.71*	1.00	-	-	-	-	-
D' (m), n=12	0.12	0.67*	0.46	0.53	-0.32	-0.15	0.63*	-0.43	-0.09	-0.26	1.00	-	-	-	-
Mean Power (W), n=29	-0.32	0.59	0.69	0.40	-0.34	-0.05	0.47	0.36	0.28	0.48	0.55	1.00	-	-	-
Peak Power (W), n=29	-0.27	0.87	0.44	0.51	-0.20	0.17	0.61	0.13	0.21	0.19	0.52	0.37	1.00	-	-
Mass-Adjusted WAnT MP (W), n=29	-0.39	0.41	0.75**	0.34	-0.40	0.00	0.40	-0.48*	0.43	0.64*	0.42	0.93	0.16	1.00	-
Mass-Adjusted WAnT PP (W), n=29	-0.59**	0.41	0.62**	0.23	-0.23	0.31	0.38	-0.42	0.62**	0.82**	0.14	0.22	0.58	0.28	1.00

**Table 2.4** Pearson correlation matrix of physiological variables, CV and D' with hill 2 climb time, \*p<0.05, \*\*p<0.01

	Hill 2 Climb Time	$\dot{V}O_2$	Mass- Adjusted $\dot{V}O_2$	$\dot{V}O_{2VSLOPE}$	Mass- Adjusted $\dot{V}O_{2VSLOPE}$	$\dot{V}O_2$ VSLOPE Stage	$\dot{V}O_{2LL}$	Mass- Adjusted $\dot{V}O_{2LL}$	$\dot{V}O_{2LL}$ Stage	CV	D'	Mean Power	Peak Power	Mass- Adjusted WAnT MP	Mass- Adjusted WAnT PP
Hill 2 Climb Time (min), n=28	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2MAX}$ (L•min <sup>-1</sup> ), n=26	0.11	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-
Mass-Adjusted $\dot{V}O_{2MAX}$ (L•min <sup>-1</sup> ), n=26	-0.13	0.59**	1.00	-	-	-	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2VSLOPE}$ (L•min <sup>-1</sup> ), n=24	-0.22	0.66**	0.54**	1.00	-	-	-	-	-	-	-	-	-	-	-
Mass-Adjusted $\dot{V}O_{2VSLOPE}$ (L•min <sup>-1</sup> ), n=24	0.34	-0.35	-0.59**	-0.91**	1.00	-	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2VSLOPE}$ Stage (km•h <sup>-1</sup> •%), n=21	-0.25	0.09	0.18	0.63**	-0.72**	1.00	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2LL}$ (L•min <sup>-1</sup> ), n=25	-0.02	0.72**	0.57**	0.41	-0.23	-0.20	1.00	-	-	-	-	-	-	-	-
Mass-Adjusted $\dot{V}O_{2LL}$ (L•min <sup>-1</sup> ), n=25	-0.18	0.28	0.66**	0.26	-0.28	-0.18	0.89**	1.00	-	-	-	-	-	-	-
$\dot{V}O_{2LL}$ Stage (km•h <sup>-1</sup> •%), n=20	0.06	0.21	0.65**	0.04	-0.14	-0.06	0.49*	0.71**	1.00	-	-	-	-	-	-
CV (m•s <sup>-2</sup> ), n=12	-0.82**	0.19	0.56	0.19	-0.29	0.07	0.31	-0.47	0.71*	1.00	-	-	-	-	-
D' (m), n=12	0.27	0.67*	0.46	0.53	-0.32	-0.15	0.63*	-0.43	-0.09	-0.26	1.00	-	-	-	-
Mean Power (W), n=29	-0.21	0.59**	0.69**	0.40	-0.34	-0.05	0.47*	0.36	0.28	0.48	0.55	1.00	-	-	-
Peak Power (W), n=29	0.38	0.87**	0.44*	0.51*	-0.20	0.17	0.61**	0.13	0.21	0.19	0.52	0.37*	1.00	-	-
Mass-Adjusted WAnT MP (W), n=29	-0.27	0.41	0.75**	0.34	-0.40	0.00	0.40	0.47*	0.43	0.64*	0.42	0.93**	0.16	1.00	-
Mass-Adjusted WAnT PP (W), n=29	0.26	0.41	0.62**	0.23	-0.23	0.31	0.38	0.43	0.62**	0.82**	0.14	0.22	0.58**	0.28	1.00

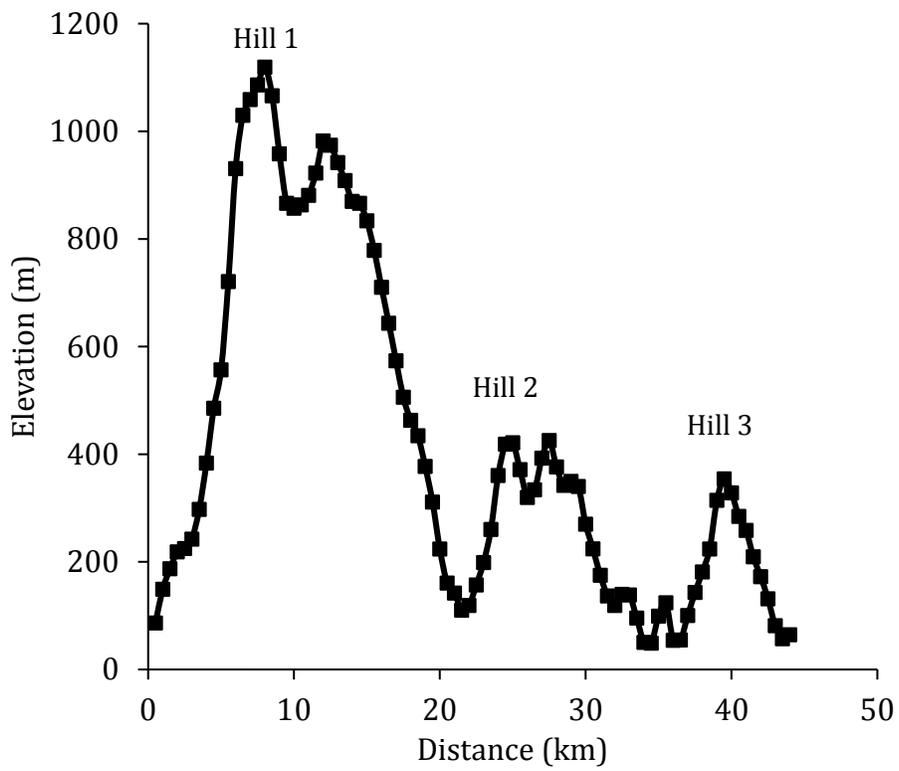
**Table 2.5** Pearson correlation matrix of physiological variables, CV and D' with hill 3 climb time, \*= $p < 0.05$ , \*\*= $p < 0.01$

	Hill 3 Climb Time	$\dot{V}O_2$	Mass- Adjusted $\dot{V}O_2$	$\dot{V}O_2$ VSLOPE	Mass- Adjusted $\dot{V}O_2$ VSLOPE	$\dot{V}O_2$ VSLOPE Stage	$\dot{V}O_{2LL}$	Mass- Adjusted $\dot{V}O_{2LL}$	$\dot{V}O_{2LL}$ Stage	CV	D'	Mean Power	Peak Power	Mass- Adjusted WAnT MP	Mass- Adjusted WAnT PP
Hill 3 Climb Time (min), n=28	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2MAX}$ (L•min <sup>-1</sup> ), n=26	-0.12	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-
Mass-Adjusted $\dot{V}O_{2MAX}$ (L•min <sup>-1</sup> ), n=26	-0.56**	0.59**	1.00	-	-	-	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2VSLOPE}$ (L•min <sup>-1</sup> ), n=24	-0.32	0.66**	0.54**	1.00	-	-	-	-	-	-	-	-	-	-	-
Mass-Adjusted $\dot{V}O_{2VSLOPE}$ (L•min <sup>-1</sup> ), n=24	0.46*	-0.35	-0.59**	-0.91**	1.00	-	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2VSLOPE}$ Stage (km•h <sup>-1</sup> •%), n=21	-0.47*	0.09	0.18	0.63**	-0.72**	1.00	-	-	-	-	-	-	-	-	-
$\dot{V}O_{2LL}$ (L•min <sup>-1</sup> ), n=25	-0.11	0.72**	0.57**	0.41	-0.23	-0.20	1.00	-	-	-	-	-	-	-	-
Mass-Adjusted $\dot{V}O_{2LL}$ (L•min <sup>-1</sup> ), n=25	-0.37	0.28	0.66**	0.26	-0.28	-0.18	0.89**	1.00	-	-	-	-	-	-	-
$\dot{V}O_{2LL}$ Stage (km•h <sup>-1</sup> •%), n=20	-0.61**	0.21	0.65**	0.04	-0.14	-0.06	0.49*	0.69**	1.00	-	-	-	-	-	-
CV (m•s <sup>-2</sup> ), n=12	-0.90**	0.19	0.56	0.19	-0.29	0.07	0.31	-0.47	0.71*	1.00	-	-	-	-	-
D' (m), n=12	0.29	0.67*	0.46	0.53	-0.32	-0.15	0.63*	-0.43	-0.09	-0.26	1.00	-	-	-	-
Mean Power (W), n=29	-0.34	0.59**	0.69**	0.40	-0.34	-0.05	0.47*	0.36	0.28	0.48	0.55	1.00	-	-	-
Peak Power (W), n=29	-0.15	0.87**	0.44*	0.51*	-0.20	0.17	0.61**	0.13	0.21	0.19	0.52	0.37	1.00	-	-
Mass-Adjusted WAnT MP (W), n=29	-0.46*	0.41	0.75**	0.34	-0.40	0.00	0.40	0.47*	0.43	0.64*	0.42	0.93	0.16	1.00	-
Mass-Adjusted WAnT PP (W), n=29	-0.56**	0.41	0.62**	0.23	-0.23	0.31	0.38	0.43	0.62**	0.82	0.14	0.22	0.58	0.28	1.00

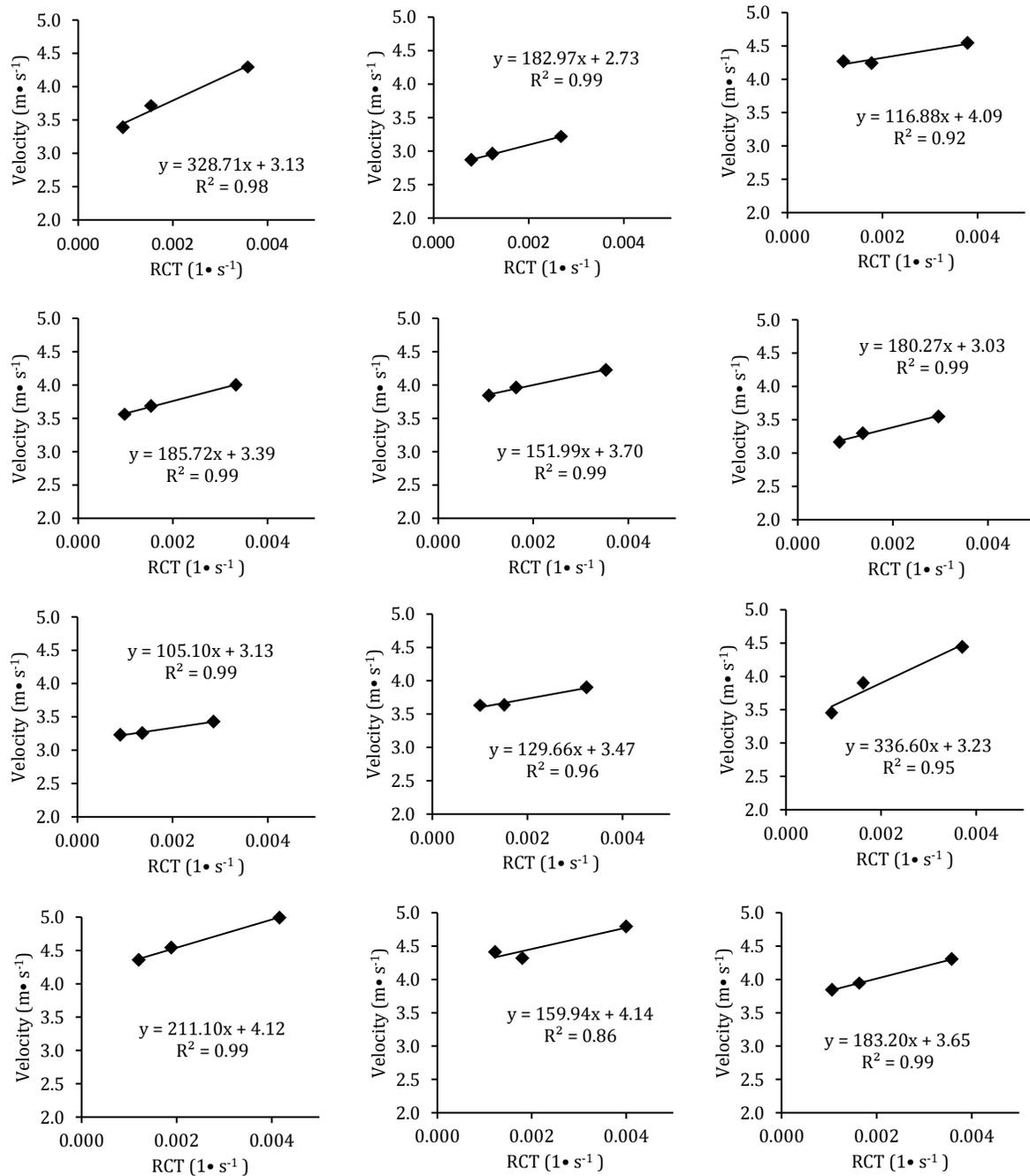
**Table 2.6** Multiple univariate linear regression of physiological variables, CV and D' with hill 3 climb time.

Regression coefficients					
CV (m•s <sup>-1</sup> )	$\dot{V}O_{2LL}$ Stage (km•h <sup>-1</sup> •%)	Intercept (min)	SE (min)	R <sup>2</sup>	p
-12.85		86.60	2.96	0.81	<0.001
-7.64	-0.13	81.09	2.25	0.90	<0.001

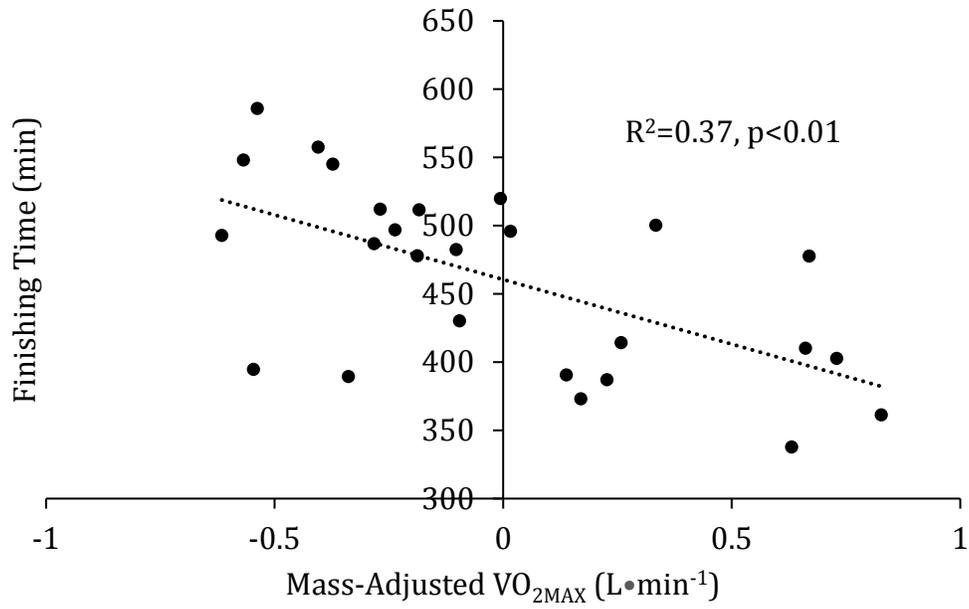
Variable values are unstandardized regression coefficients, n=10. CV = Critical velocity.



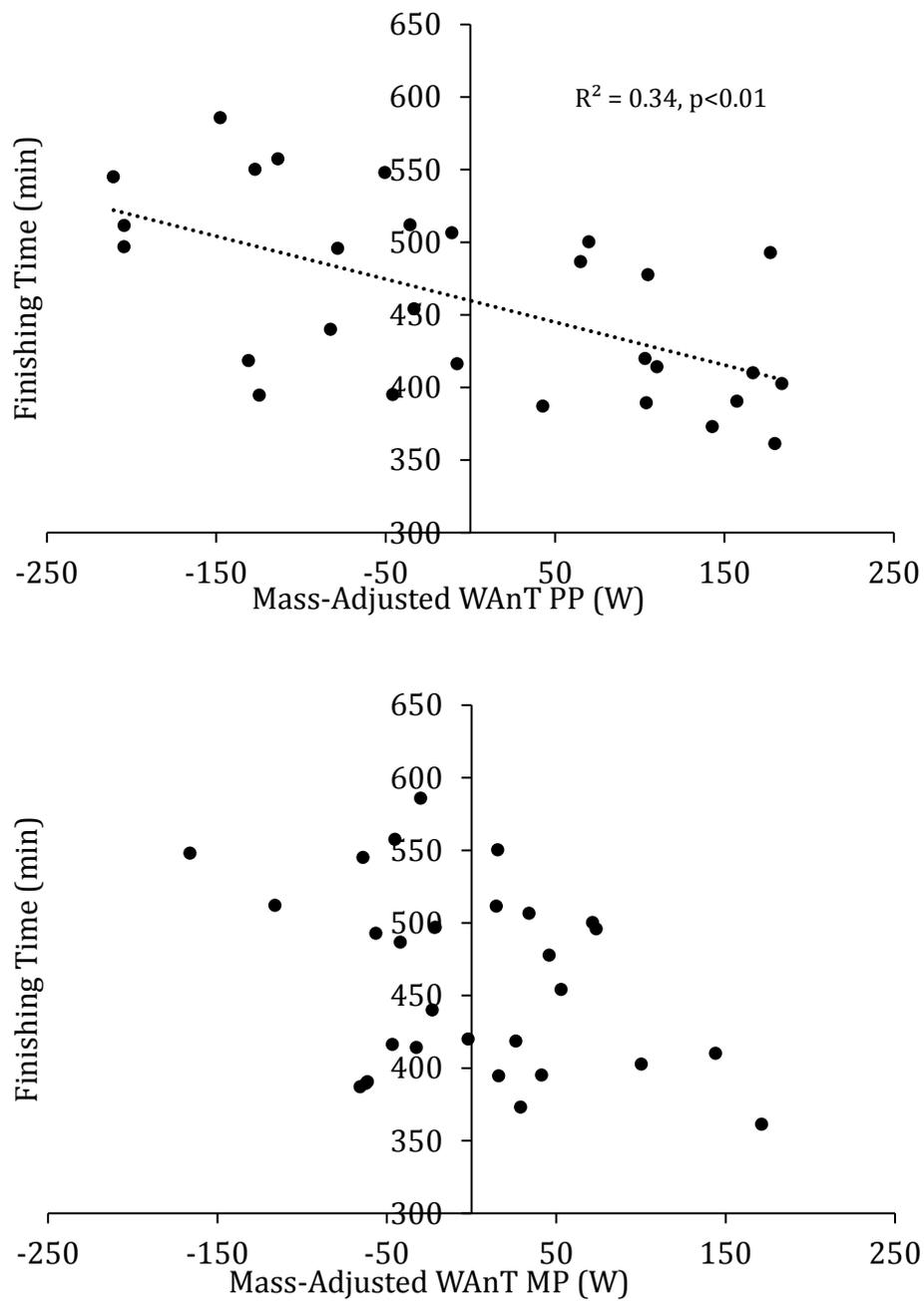
**Figure 2.1** Race course elevation profile. Hill 1 = Black Mountain, hill 2 = Grouse Mountain, hill 3 = Seymour Grind.



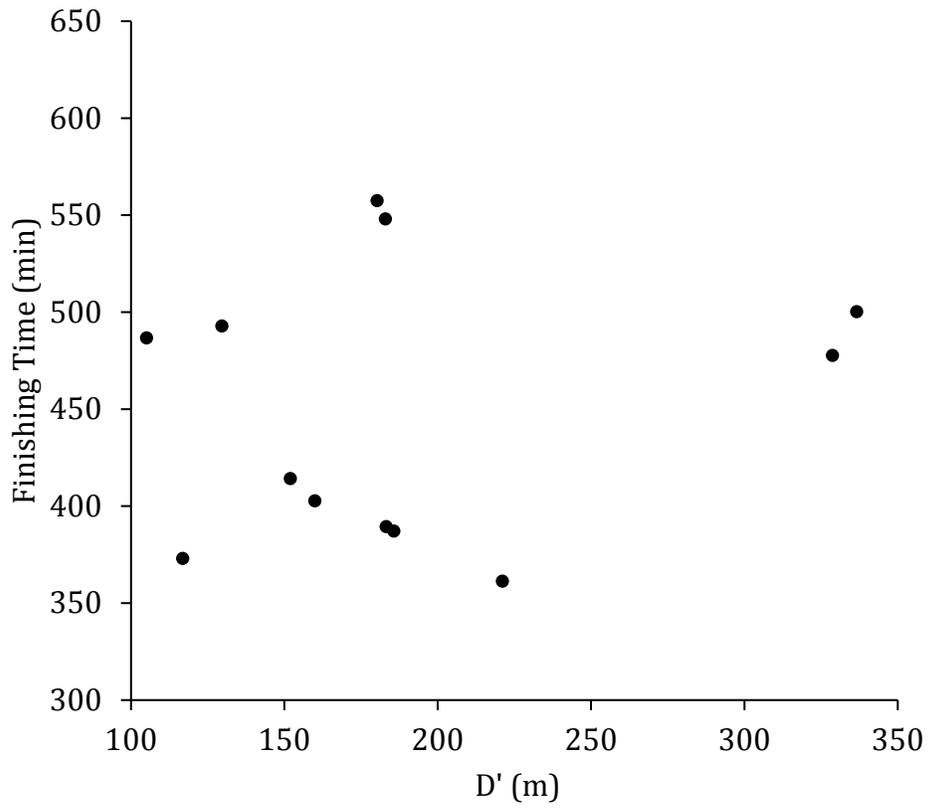
**Figure 2.2** Running velocities from the critical velocity (CV) test on the track plotted against the reciprocal of completion times (RCT) for each of the three distances (1200 m, 2400 m and 3600 m). The linear regression equations were used to estimate the CV and D' for each runner, whereby the slope of the plot gives individual D' values in meters. Each plot features the data of a single participant.



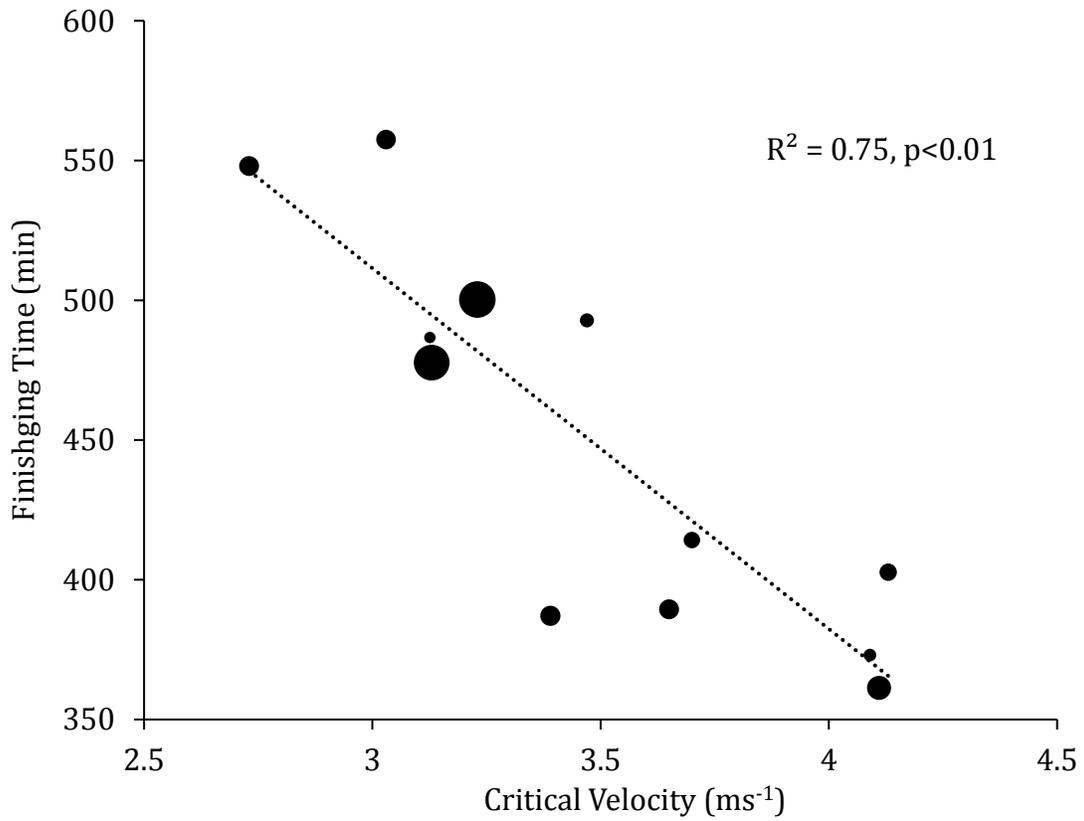
**Figure 2.3** Finishing time plotted as a function of mass-adjusted  $\dot{V}O_{2MAX}$ . Regression line equation: Finishing time (min) =  $-95.7 \cdot \text{mass-adjusted } \dot{V}O_{2MAX} \text{ (L}\cdot\text{min}^{-1}) + 460.5$ ,  $p < 0.01$ .  $n = 26$ .



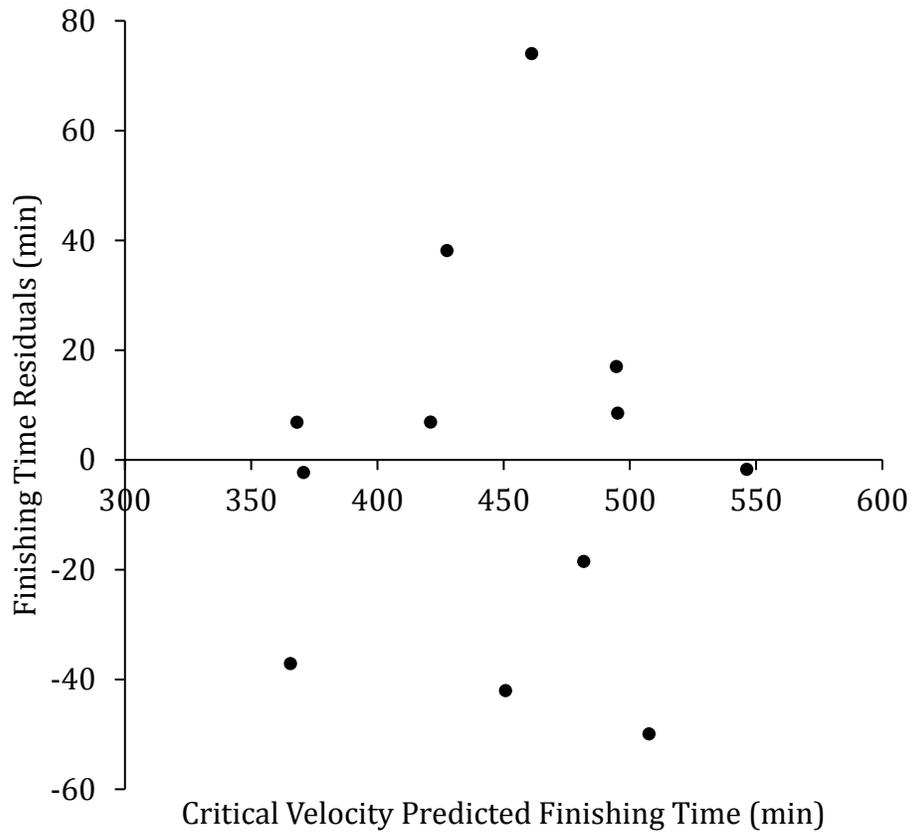
**Figure 2.4** Finishing time plotted as a function of both mass-adjusted WAnT peak power (upper panel) and mass-adjusted WAnT mean power (lower panel);  $n=29$  both panels. Top panel regression line equation: Finishing time (min) =  $-0.30 \cdot \text{WAnT PP (W)} + 459.8$ ,  $p < 0.01$ .



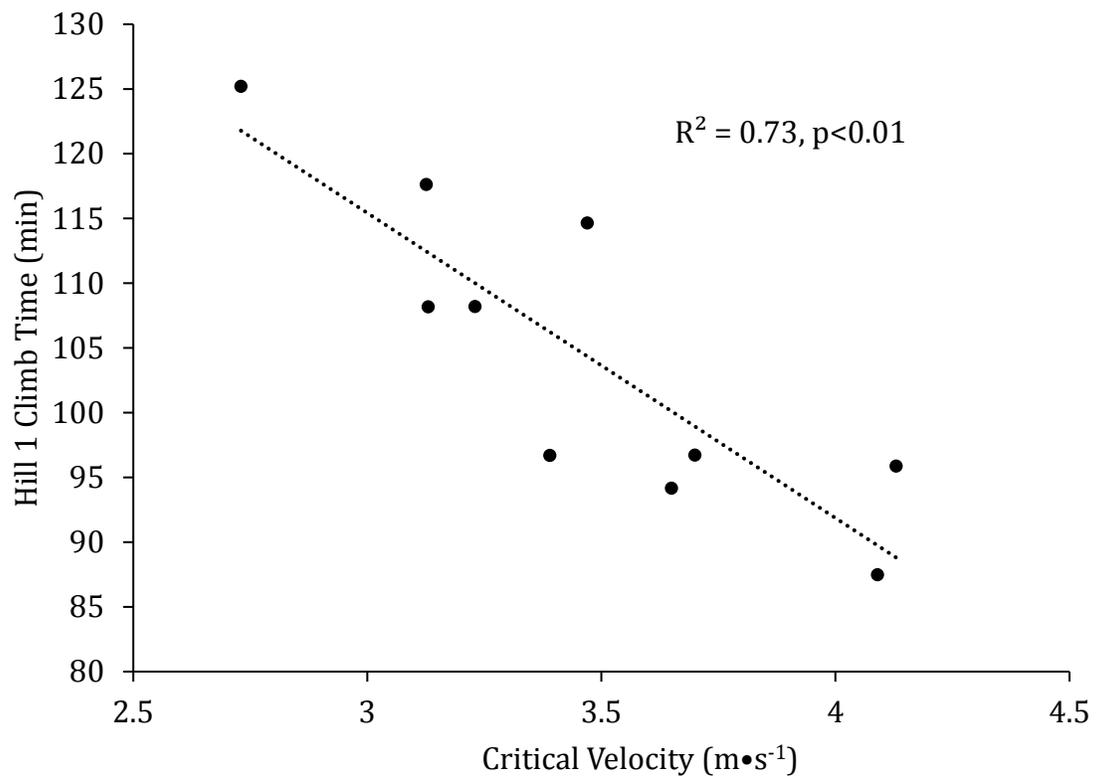
**Figure 2.5** Plot of finishing time as a function of D'; n=12, p>0.05.



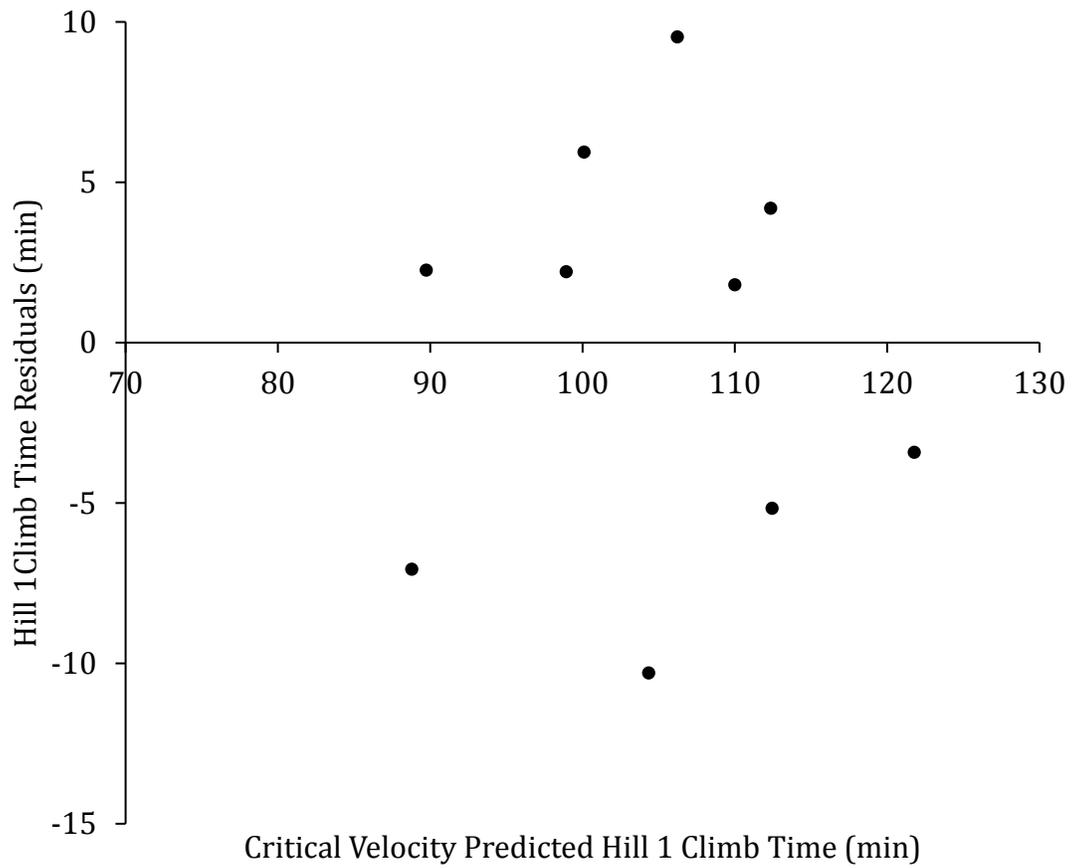
**Figure 2.6** Finishing time plotted as a function of CV; n=12. Regression line equation: Finishing time (min) =  $-0.129.1 \cdot CV \text{ (m}\cdot\text{s}^{-1}) + 898.7$ ,  $p < 0.01$ . The size of the markers are scaled by width to represent the magnitude of D', where a larger marker area corresponds to a greater D' value.



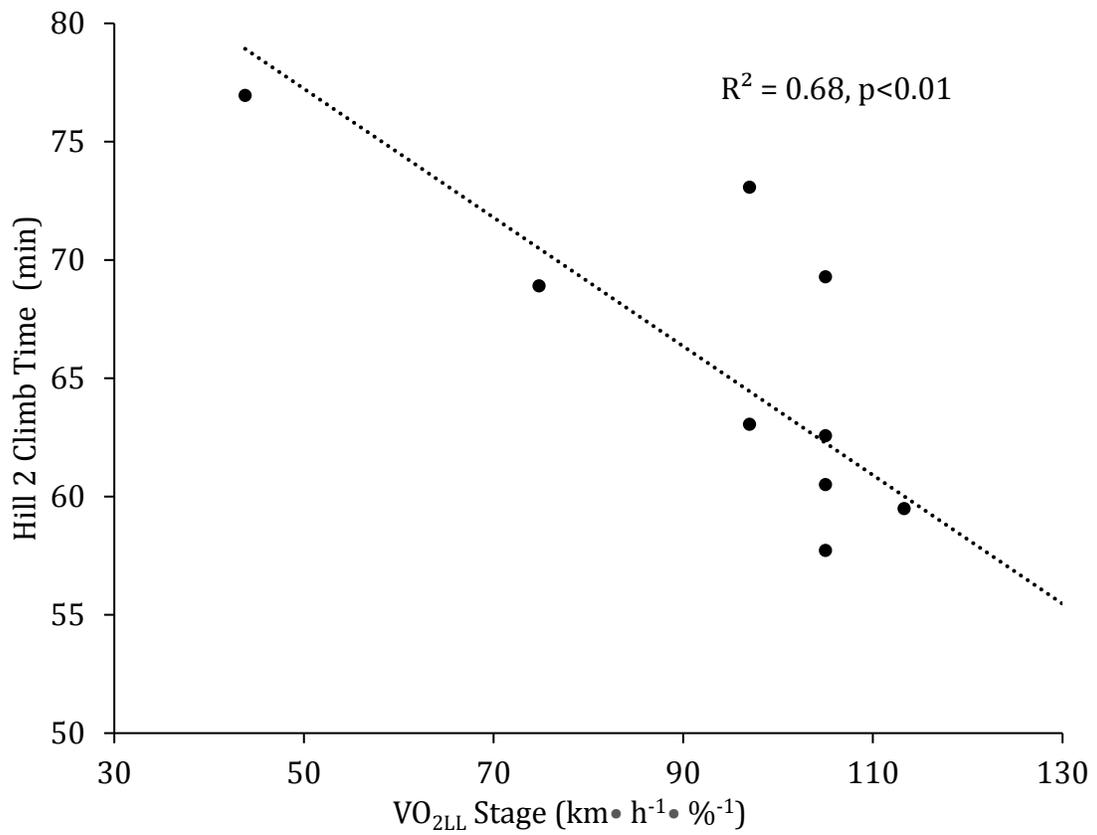
**Figure 2.7** Residual analysis for the goodness of fit of the first order linear regression model for finishing time plotted as a function critical velocity predicted finishing time. Finishing time residuals = critical velocity predicted finishing time – actual finishing time; Shapiro-Wilk’s analysis ( $p=0.88$ ),  $n=12$ .



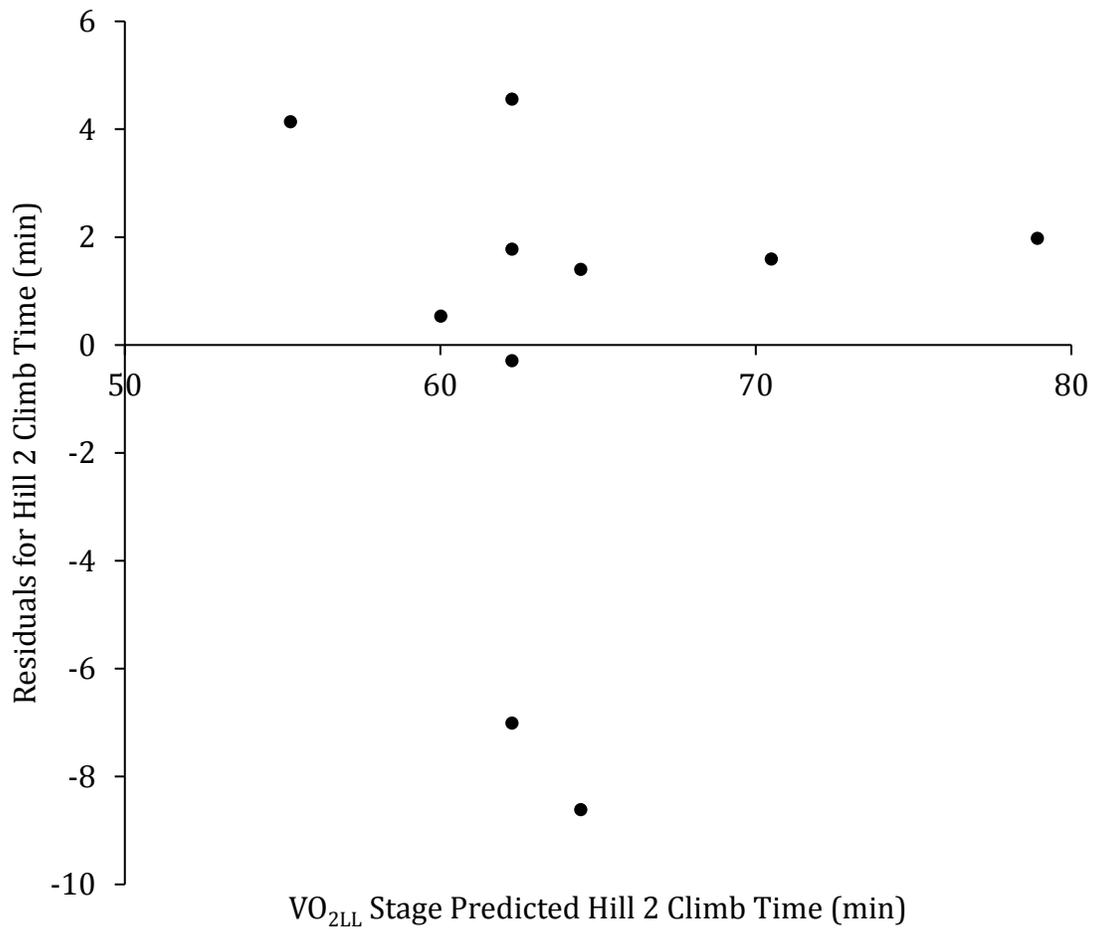
**Figure 2.8** Hill 1 climb time plotted as a function of critical velocity. N =10. Regression line equation: Finishing time (min) = -23.6•CV (m•s<sup>-1</sup>) + 186.1, p<0.01.



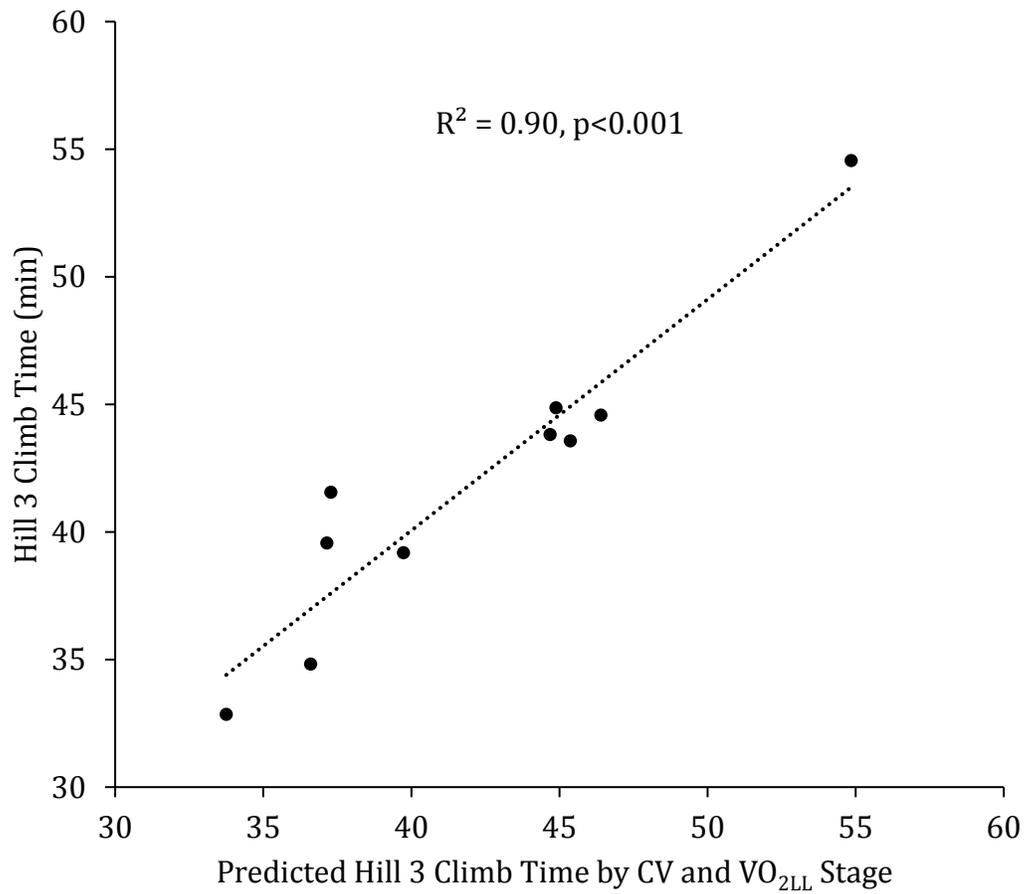
**Figure 2.9** Residual analysis for the goodness of fit of the first order linear regression model for hill 1 time plotted as a function critical velocity predicted hill 1 climb time. Hill 1 climb time residuals = critical velocity predicted hill 1 climb time – actual hill 1 climb time; Shapiro-Wilk’s analysis ( $p=0.60$ ),  $n=10$ .



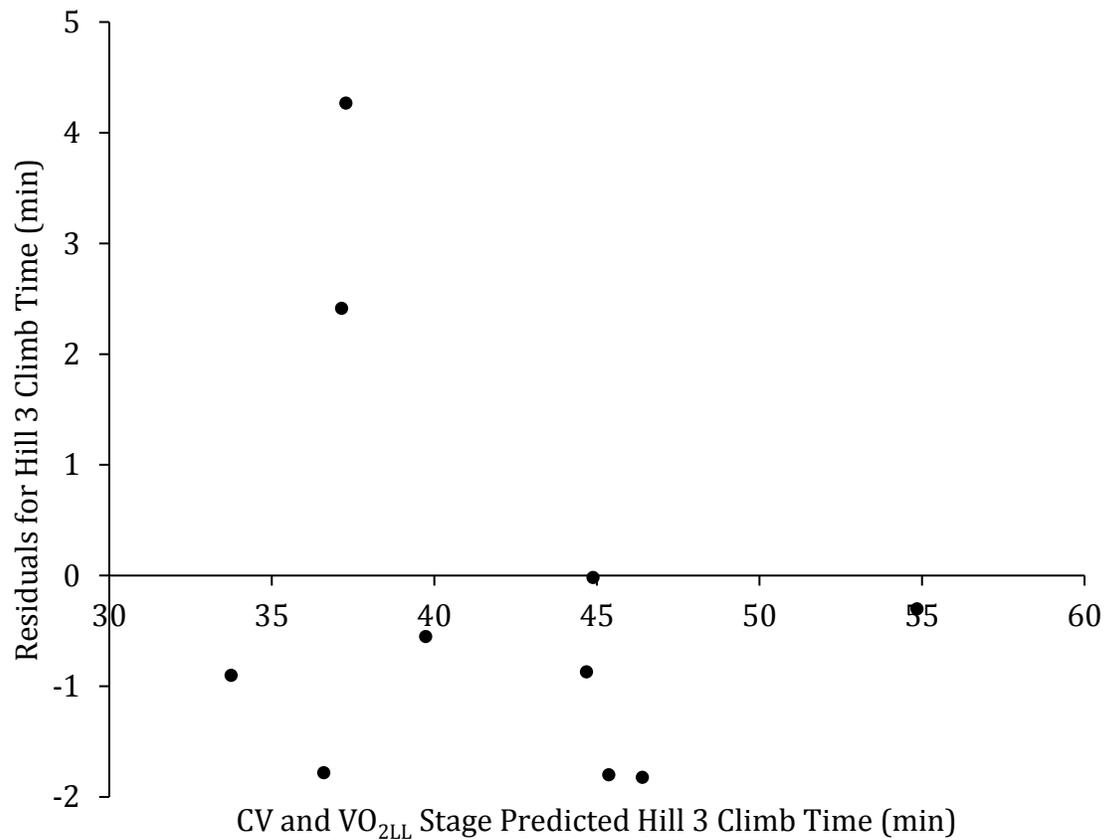
**Figure 2.10** Hill 2 climb time plotted as a function of  $VO_{2LL}$  Stage. N =10. Regression line equation: Finishing time (min) =  $-0.27 \cdot CV (\text{m} \cdot \text{s}^{-1}) + 90.1$ ,  $p < 0.01$ .



**Figure 2.11** Residual analysis for the goodness of fit of the first order linear regression model for from the first order regression of hill 2 climb time plotted as a function  $\dot{V}O_{2LL}$  Stage predicted hill 2 climb time; hill 2 climb time residuals =  $\dot{V}O_{2LL}$  stage predicted hill 2 climb time – actual hill 2 climb time; Shapiro-Wilk's analysis ( $p=0.14$ ),  $n=10$ .



**Figure 2.12** Hill 3 climb time as predicted by a two-variable regression of CV and VO<sub>2LL</sub> Stage; n=10. Regression line equation: Finishing time (min) = -0.91X + 3.8, p<0.001.



**Figure 2.13** Residual analysis for the goodness of fit of the first order linear regression model for from the first order regression of hill 3 climb time plotted as a function CV and  $\dot{V}O_{2LL}$  Stage predicted hill 3 climb time; hill 3 climb time residuals = CV and  $\dot{V}O_{2LL}$  stage predicted hill 2 climb time (as predicted by equation 1) – actual hill 2 climb time; Shapiro-Wilk’s analysis ( $p=0.02$ ),  $n=10$ .

## Chapter 3.

# Prediction of mountain ultra marathon performance with anthropometric variables

### 3.1. Introduction

While variables such as  $\dot{V}O_{2MAX}$ , lactate threshold, and running economy are important predictors of endurance performance (Lazzer et al. 2012, Coyle 1995, Bassett and Howley 2000), anthropometric variables including % body fat also have been shown to predict performance in a range of endurance and ultra-endurance sports including cycling, skating, and iron-distance events (Hoffman 2008, Knechtle 2014, Barandun et al. 2012). In the 161 km Western States Endurance Race, it was observed that a sample of 310 male MUM runners featured greater and more varied body mass indexes (BMI), of  $\sim 23$  (range 18-31)  $\text{kg}\cdot\text{m}^{-2}$ , than road-running marathoners who had BMI of  $\sim 20$   $\text{kg}\cdot\text{m}^{-2}$  (range 19-22) (Hoffman 2008). Hoffman et al. (2008) estimated this typical road-running marathoner body type from a collection of 9 studies of middle to marathon-distance runners, and this comparison suggests that the anthropometric characteristics of MUM runners may be different from that of road marathoners.

To investigate anthropometry and MUM performance, limb girths and surface-area-to-body-mass ratio ( $A_{DM}^{-1}$ ) were assessed as predictors of MUM finishing and hill climb times. The importance of lower-limb girth measures in MUM performance has been debated from both running-economy (Cureton and Sparling 1980) and physiological points of view. A larger girth generally represents a greater overall body mass and that gives a higher energy cost of running (Cureton and Sparling 1980). Conversely, more muscle mass would allow for greater storage of adenosine triphosphate (ATP), creatine phosphate (PCr) and glycogen (Miura et al. 2002, Fairchild et al. 2002), which could enhance aerobic and anaerobic performance by providing a

greater fuel reserve for the duration of the race (Fairchild et al. 2002). This potential relationship between a larger girth and anaerobic performance has been supported by positive significant associations between muscle cross-sectional area (CSA) and  $W'$  (Miura et al. 2002), as well as an effect of increased glycogen stores to increase both anaerobic capacity (Miura et al. 2000) and hypothetically endurance performance by prolonging the time point of muscle glycogen depletion (Rapoport 2010). With respect to anaerobic work capacity and power both lean body mass in active men (Maciejczyk et al. 2015) and specifically lean lower body mass in active women (Perez-Gomez et al. 2008) predict higher peak power outputs in the Wingate anaerobic test and faster 300-m sprinting performance (Perez-Gomez et al. 2008). Indeed, as mentioned above, the previous investigation of ultra-runners indicates that a higher overall BMI is observed in these populations in comparison to standard marathon participants (Hoffman 2008). Based on these observations, Hoffmann et al. (2008) suggested that “additional body mass is not necessarily such an disadvantage in a long hilly running event” (Hoffman 2008). However, measures of increased adiposity such as body fat percentage (Knechtle 2014) or endomorphy (Vernillo et al. 2013, Kandel, Baeyens, and Clarys 2014) have both been associated with slower race times in endurance events, the rationale being that excess fat mass would detrimentally effect running economy (Cureton and Sparling 1980) and therefore performance. For example, a study of Ironman competitors found that as the endomorphy of athlete was lower their race time was significantly faster (Kandel, Baeyens, and Clarys 2014). Therefore, although it is recognized here that a relationship between CSA and MUM finishing time should not be assumed to be linear due to the increased metabolic cost of movement of a larger body mass, it is suggested that within this sub-population of MUM runners that increased lower-limb girth measures could be advantageous through the mechanisms of increased anaerobic capacity and glycogen supply. In addition, a larger muscle glycogen supply relative to a given body mass in a MUM runners could also improve endurance performance.

A positive relationship between race finish line ambient temperature and finishing time has been shown to exist in ultra-running (Wegelin and Hoffman 2011) and it is generally accepted that hyperthermia inhibits endurance exercise performance (González-Alonso et al. 1999, Nybo 2008). Accordingly, the possibility exists that anthropometric variables that aid to maintain core temperature in the face of heat stress

are advantageous for success in MUM events (Marino et al. 2000). Both a lower body mass (Marino et al. 2000) and greater surface-area-to-body-mass ratio have been shown to predict a lower core temperature during running under hot conditions. Marino et al. (2000) reported  $A_{DM}^{-1}$  explained 18% of the variance in body heat storage in 25°C and 59% in 35°C environments (Marino et al. 2000), indicating a greater  $A_{DM}^{-1}$  gives a lower heat storage. These results are further supported by findings of Epstein et al. (1983) which found that a combination of  $A_{DM}^{-1}$  and work efficiency explained 53% of the variance in rectal temperature in males exercising during heat stress (Epstein, Shapiro, and Brill 1983), with a higher  $A_{DM}^{-1}$  giving a lower rectal temperature. Therefore, the variable of  $A_{DM}^{-1}$  may allow for improved MUM performance by helping to maintain a lower core temperature.

Based on the above rationale, the current study had four hypotheses for MUM runners with high aerobic power. Firstly, that a greater lower-limb girth would be associated with a faster finishing time, as well as faster times during the uphill portions of the race. Secondly, that surface-area-to-body-mass ratio would be negatively associated with finishing time. Thirdly, that those with a lower endomorphy would be associated with a faster finishing time, as well as faster times during the uphill portions of the race. Finally that those with a lower body fat percentage would be associated with a faster finishing time, as well as faster times during the uphill portions of the race.

## **3.2. Methods**

### **3.2.1. Participants**

Thirty-four healthy participants, seven females and 27 males, volunteered to participate in this study, this group was the same cohort as chapter 2. Table 3.1 shows their age and anthropometric characteristics.

The hypothesised effect size for the outcome variables of lower-limb girth and  $A_{DM}^{-1}$  was determined from previous studies as shown in Table 3.2. An alpha of 0.05 and a power of 80% was used, and 32 participants were determined to be required to detect an association between these variables and MUM finishing time. Each participant

received an orientation of the laboratory and a 24-h reflection period, after which each participant was required to complete a PAR-Q and a signed informed consent form. The SFU Office of Research Ethics approved this study. Each volunteer was a participant in the Knee Knackering North Shore trail race (KKNSTR).

### **3.2.2. Instrumentation**

Somatotypes and anthropometric characteristics were determined using the Heath-Carter somatotype method (Carter 2002). The equipment used included a digital scale (7540EF Electronic Glass Scale, Taylor, ON), bone calipers (Mitutoyo, Japan), a tape measure, and skinfold calipers (JBB Ltd, England). Stature was measured using a stadiometer.

### **3.2.3. Protocol**

#### ***Anthropometric Measurements***

Measurements were made of each participant's mass and stature. Skinfolts were taken at the triceps, biceps, front thigh, medial calf, forearm, subscapular, suprailiac and supraspinale measurements sites. Biepicondylar widths of the humerus and femur were measured. Girth measurements were taken of the thigh, medial calf, flexed arm, and relaxed arm. The DuBois and DuBois formula (Du Bois and Du Bois 1989) was employed to estimate body surface area (BSA).

#### ***Mountain Ultra Marathon Course and Conditions***

Each volunteer was a participant in either the 2014, 2015 or 2016 Knee Knackering North Shore Trail Run (KKNSTR) race. This race was founded in 1989 and has rapidly grown from 8 to ~262 participants per year. The course contains a cumulative ~ 2400 meters of ascent and a cumulative ~ 2500 meters of descent. The course terrain is highly variable, with steep, unstable surfaces, rocks, roots and other obstacles to navigate. During the first year in 2014 the weather was warm and sunny with dry bulb temperatures (DBT) ranging from ~17-35°C and a relative humidity (RH) of ~55%, the second year in 2015, there was overcast with DBT remaining at ~10-12°C

and an RH of ~90%, and finally the third year in 2016 there was heavy rainfall with DBT of ~14-20°C and ~100% RH. All athletes had access to 11 aid stations along the course.

The course included three main ascents as shown in Fig. 2.1. The first and the largest ascent is Black Mountain (hill 1) with a climb of approximately 1000 m. The second major ascent is located from just after Cleveland Dam and the aid station at the course mid-distance point and Grouse Mountain (hill 2), has an elevation change of approximately 300 m. The last major ascent is the Seymour Grind (hill 3), which ascends about 300 m. Hill climb times were determined from Polar V800 data and defined as the elapsed time each participant spent on these 3 longest uphill sections of the course. Hill 1 was ~8 km in length from the start line, hill 2 was ~ 3 km in length and towards the middle of the race, and hill 3, the final main ascent before the end of the race, was ~3 km in length.

### **3.2.4. Statistical Analysis**

Pearson product moment correlations, univariate linear regression analysis, as well as multiple univariate stepwise linear regression analysis were employed to assess the relationship between anthropometric variables and the dependent variables of MUM finishing time and hill climb times. Independent variables included body mass, body mass index, lower-limb girths, somatotypes, body fat percentage, surface area, and surface-area-to-body-mass ratio. In addition to these variables a mass-adjusted surface area variable was also added by regressing surface area against body mass and then residuals of this variable was regressed against finishing time and hill climb times. The purpose of including this variable was to allow for an evaluation of surface area with a control for body mass (Tanner 1949, Packard, Birchard, and Boardman 2011). For each regression model, there was only one dependent outcome variable being predicted. For further details describing the statistical methodology used in this chapter, as well information on the construction of graphs, please refer to Appendix A. The equations that were applied to determine somatotypes (Carter 2002), body surface area (Du Bois and Du Bois 1989), and body fat percentage (Peterson, Czerwinski, and Siervogel 2003) are shown in table 3.3.

Residual analysis for the goodness of fit was employed to confirm a normal distribution of the residuals. This was done in two ways. Firstly there was a visual inspection of the residuals. Secondly, a Shapiro-Wilks' (W) test was employed. The criterion of this test was a p-value of 0.05 or greater, where the null hypothesis was a normal distribution of the residuals (Ghasemi and Zahediasl 2012).

### **3.3. Results**

#### **3.3.1. Anthropometric Outcome Measures**

Somatotype assessment results were an endomorphy of 3.1 (0.8) (mean (SD)), mesomorphy of 4.4 (1.1), and ectomorphy of 2.9 (1.2). For the 34 participants body fat was estimated to be 20.7 (4.6) %, height was 1.8 (0.1) m, body mass was 70.8 (9.7) kg, BMI was 22.4 (2.4) kg•m<sup>-2</sup> and age 46.5 (9.3) years (Table 3.1). Body surface area was found to be 1.8 (0.2) m<sup>2</sup> and surface-area-to-body-mass ratio of 1.20 (0.08) x 10<sup>-2</sup> m<sup>2</sup>•kg<sup>-1</sup> (Table 3.1). Girth measurements showed a thigh girth of 55.2 (5.2) cm and calf of 37.9 (2.4) cm.

#### **3.3.2. Prediction of Overall Race Time**

For MUM finishing time, the anthropometric variables evaluated (Table 3.4) showed significant positive correlations for endomorphy ( $r = 0.51$ ,  $p < 0.01$ ), BF% ( $r = 0.59$ ,  $p < 0.01$ ) and BMI ( $r = 0.37$ ,  $p < 0.05$ ), and a significant negative correlation was evident for finishing time and ectomorphy ( $r = -0.42$ ,  $p < 0.01$ ) and mass-adjusted surface area ( $r = -0.35$ ,  $p < 0.05$ ).

In multiple univariate stepwise linear regression analysis body fat percentage was the sole anthropometric predictor of finishing time ( $R^2 = 0.34$ ); the slope of 8.1 (SE 2.0) min•BF%<sup>-1</sup> was found to be significantly different from zero ( $p < 0.001$ ) (Fig. 3.2). Homoscedasticity and a normal distribution were observed in the residuals from a plot of finishing time as a function of BF% as supported by the Shapiro-Wilk's analysis (Fig 3.3) ( $p = 0.17$ ).

### 3.3.3. Prediction of Hill Climb Times

A first-order Pearson product moment correlation matrix (Table 3.5) showed significant correlations of endomorphy ( $r=0.56$ ,  $p<0.01$ ), ectomorphy ( $r=-0.46$ ,  $p<0.05$ ) and BF% ( $r=0.62$ ,  $p<0.01$ ) with hill 1 climb time. In multiple univariate stepwise linear regression analysis BF% was the sole predictor of hill 1 climb time ( $R^2=0.38$ ,  $p<0.001$ ); the slope of 1.8 (SE 0.4) min•% was found to be significantly different from zero ( $p<0.001$ ) (Fig 3.4). Homoscedasticity and a normal distribution were observed in the residuals from a plot of hill 1 climb time as a function of BF% as supported by the Shapiro-Wilk's analysis (Fig 3.5) ( $p=0.13$ ).

A first-order Pearson product moment correlation matrix (Table 3.6) showed a sole significant positive association of endomorphy ( $r=0.38$ ,  $p<0.05$ ) with hill 2 climb time. In multiple univariate stepwise linear regression analysis endomorphy was the sole predictor of hill 2 climb time ( $R^2=0.15$ ,  $p=0.04$ ); the slope of 6.0 (SE 2.8) min was found to be significantly different from zero ( $p=0.04$ ) (Fig 3.6). Homoscedasticity and a normal distribution were observed in the residuals from a plot of hill 2 climb time as a function of endomorphy as supported by the Shapiro-Wilk's analysis (Fig 3.7) ( $p=0.63$ ).

A first-order Pearson product moment correlation matrix (Table 3.7) showed associations of endomorphy ( $r=0.51$ ,  $p<0.01$ ) and BF% ( $r=0.63$ ,  $p<0.01$ ) with hill 3 climb time. In multiple univariate stepwise linear regression analysis BF% was the sole predictor of hill 3 climb time ( $R^2=0.40$ ,  $p<0.001$ ); the slope of 0.79 (SE 0.19) min•%<sup>-1</sup> was found to be significantly different from zero ( $p<0.001$ ) (Fig 3.8). Homoscedasticity and a normal distribution were observed in the residuals from a plot of hill 3 climb time as a function of % BF as supported by the Shapiro-Wilk's analysis (Fig 3.9) ( $p=0.22$ ).

## 3.4. Discussion

The main finding of this study is that body-fat percentage significantly explained some variance of MUM race finishing time and the two of the three main hill climb times in the MUM. Endomorphy was found to predict the second hill climb time of the race. Consequently, these results do not support the hypothesis that a greater lower-limb girth would be associated with a faster finishing time as well as hill climb times. The

hypothesis that those with a greater surface-area-to-body-mass ratio would be associated with a faster finishing time was not evident in the analysis, however after adjusting for mass a significant correlation was observed between surface-area and finishing time.

A lower body fat percentage is well supported to give an advantage in both marathons and ultra-marathons (Tanda and Knechtle 2015, Knechtle, Knechtle, Barandun, et al. 2011, Tanda and Knechtle 2013). Tanda and Knechtle combined data from 52 male marathoners, and 135 male ultra runners to show a consistent significant positive relationship between body fat percentage and race time, with 36% of the variance explained in finishing time for the 42 km event and 26% explained for the 100 km event (Tanda and Knechtle 2015). In 42 female half-marathon runners a positive relationship was also found between body fat percentage and finishing time ( $R^2=0.31$ ,  $p<0.001$ ) (Knechtle, Knechtle, Barandun, et al. 2011), which is comparable to the relationship we have found in the current study where 34% of the variance in the finishing time was explained by BF%. A recent review of endurance performance concluded that a low body-fat percentage was the main anthropometric variable for ultra-endurance performance (Knechtle 2014). This relationship of a lower BF% with better performance, however, is not always evident for ultra-endurance runners (Knechtle et al. 2010). Knechtle et al. (2010) suggested this finding was due to their population of male runners, although they did not put forward any further explanations for this result. One possibility is that in this subgroup of participants that the volume of training which might result in a lower BF% was more important than BF% itself for success in their ultra-endurance event (Legaz and Eston 2005), or that in ultra-endurance events that within a certain range BF% represents a necessary store of energy for use during the race (Hoffman 2008). Knechtle et al.'s (2010) findings are contradicted by our current results which reinforce the hypothesis that BF% is an important factor in not only endurance but also specifically MUM success.

The BMI results support previous findings that 161 km ultra-endurance trail runners had a generally higher BMI of  $\sim 23 \text{ kg m}^{-2}$  in the male participants, compared to their road marathon counterparts who generally have a BMI of  $\sim 20 \text{ kg m}^{-2}$  (Hoffman 2008). Hoffman (2008) suggested that the need for greater energy stores during such a long race predispose this group to have a higher BMI (Hoffman 2008). It should be

noted, however, that to our knowledge it has not yet been confirmed if this difference in BMI represents a possible advantage as described above, or is simply due to the possibility that MUM runners could represent a more recreational group in some cases. Regardless of this possibility, despite this higher BMI in ultra-endurance trail runners, it appears that a lower BMI may be advantageous as it was demonstrated to be associated with better ultra-marathon performance (Hoffman 2008). Our results support these findings with a positive significant correlation ( $r=0.37$ ,  $p<0.05$ ) being found between finishing time and BMI. It must be noted, however, that this observation is not without exception, as others studies have not found associations between BMI and ultra marathon performance even with samples sizes from 63 to 81 runners that gave a high power to these study designs (Knechtle, Knechtle, Rosemann, and Senn 2011, Knechtle, Knechtle, Rosemann, and Lepers 2011). Furthermore, limitations exist with the use of BMI as an index of physique including that this ratio gives only moderate ( $R^2=0.25$ ) correlations to body adiposity (Ross et al. 1988). This finding suggests that other metrics of body composition of MUM runners, such as DXA, may be needed to resolve better how physique is related to the performance of these athletes.

Surface-area-to-body-mass ratio has not been previously investigated in the context of mountain ultra marathons. Marino et al. (2000) investigated if a higher surface-area-to-body-mass ratio would be advantageous for trail runners in hot and humid conditions (Marino et al. 2000). Their results showed a negative relationship between  $A_{DM}^{-1}$  and heat storage during moderate exercise in 25°C and 35°C, presumably because of a greater surface area per kg to allow for greater heat loss through evaporative cooling (Marino et al. 2000). Epstein et al.'s (1983) findings have further supported this relationship. In this study 23 males completed a step test in 40°C and 40% RH (Epstein, Shapiro, and Brill 1983). It was found using multiple linear regression that  $A_{DM}^{-1}$  and work efficiency explained 19% of the variance in heat storage and 53% of the variance in rectal temperature, where a greater  $A_{DM}^{-1}$  predicted a lower heat gain or rectal temperature. This negative relationship is, however, is not always observed. For example, a previous study in which 19 men and 8 women completed a 1 hour exercise trial on a cycle ergometer at low intensity (Havenith, Luttikholt, and Vrijkotte 1995). In this study exercise was completed under high environmental heat stress, specifically at 35°C and 80% relative humidity (Havenith, Luttikholt, and Vrijkotte

1995). Here a positive relationship ( $R^2 > 0.35$ ,  $p < 0.001$ ) was found between  $A_D \cdot m^{-1}$  and rectal temperature (Havenith, Luttikholt, and Vrijkotte 1995). These results might be explained by the high ambient temperature and relative humidity in the study which could cause heat to be gained, instead of lost, from the skin in these conditions. It should be emphasized, however, that in these studies the exercise intensity used might represent a different metabolic demand, and therefore thermoregulatory response than endurance events where the metabolic demand could be lower. Furthermore, even in these time to exhaustion experiments anthropometry only predicts heat gain in heat stressed environments (Marino et al. 2000). Therefore, caution should be given when applying the results of these tests to ultra endurance competitions.

Although the relationship between  $A_D \cdot m^{-1}$  and heat storage is yet to be fully resolved, hyperthermia during exercise has been thoroughly documented to inhibit endurance performance (González-Alonso et al. 1999, Nybo 2008). As summarized in Nybo's (2008) review of hyperthermia and fatigue, the main mechanism for hyperthermia-induced fatigue during endurance events is thought to be central fatigue, which impairs the brain's ability to recruit motor neurons fully (Nybo 2008). An example of this effect is a study in which 14 endurance-trained cyclists conducted maximal voluntary isometric contractions and electrically stimulated contractions of the leg extensors (Nybo and Nielsen 2001). These contractions were completed before and after a 1-hr cycling trial in either normothermic (18°C) or hyperthermic (40°C) conditions and both integrated surface electromyography and force were among the variables measured. The voluntary activation percentage was ~28% lower in the hyperthermic condition as compared to normothermia, and integrated surface electromyography was also found to be significantly lower (Nybo and Nielsen 2001). Other proposed mechanisms for hyperthermia-induced fatigue include increased glycogen usage and impaired cardiovascular function (González-Alonso et al. 1999, Fernández-Elías et al. 2015). Indeed, both time to exhaustion in a cycle ergometer exercise trial and  $\dot{V}O_{2MAX}$  during a ~3-6 min maximal cycle ergometer test have been shown to be reduced in hyperthermic conditions relative to normothermia (González-Alonso et al. 1999, Nybo et al. 2001). Specifically, with regards to the reduction in  $\dot{V}O_{2MAX}$ , an esophageal temperature 1°C above normal resting values and a skin temperature ~7°C higher caused a ~0.5 L·min<sup>-1</sup> reduction in  $\dot{V}O_2$  (Nybo et al. 2001). The importance of surface-

area-to-body-mass ratio and hyperthermia-induced limitations to performance can be questioned for the current study as the majority of our participants competed in MUMs with cool conditions. During the first year DBT ranged from ~17-35°C, however, the second year DBT remained at ~10-12°C, and in year three the DBT was ~14-20°C. These conditions and their variation from year-to-year might explain the of correlation mass-adjusted surface area, but not between  $A_{DM}^{-1}$ , and finishing time in this study. Based on previous findings it could be concluded that temperature conditions during the second year were ideal while the first and third year would present with moderate to mild heat stress and therefore hindrance of performance (Galloway and Maughan 1997). Unfortunately, the sample size of 5 was too small to conduct a reliable separate analysis for the first year alone where heat stress was high. Future studies could specifically investigate the role of  $A_{DM}^{-1}$ , or mass-adjusted surface area, in MUMs with higher heat stress.

For all significant anthropometric associations to MUM finishing time from the regression analysis, a common theme has appeared that those with lower fat mass and leaner body type had an advantage in a MUM. This theme is supported by our findings that overall race time was associated with BF%, endomorphy, ectomorphy and body mass index. Mechanistically, this finding is well supported because it has been shown that even small increases in mass greatly decrease performance in running (Cureton and Sparling 1980). In male runners, a ~7.5% increase in excess weight added during a 12-minute run results in a 30% decrease in the distance run (Cureton and Sparling 1980). Furthermore, the negative effects of additional mass would be compounded in a MUM where the metabolic cost of movement is increased by the high grades of the course (Minetti et al. 2002), which were ~14% for hill 1, ~11% for hill 2 and ~10% for hill 3. Based on these findings, it appears that in these selected, on average cool, conditions factors pertaining to the cost of movement might be more important than thermoregulation.

### ***Future Directions***

As in the previous chapter, several recommendations can be made based on our current results. Firstly, as mentioned above, DXA could be applied in lieu of BMI to more directly and accurately determine the adiposity of athletes in the race. Another approach

could be to investigate an experimental group with a larger range in body fat percentage or BMI, not only could this better determine if either of these factors is related to performance but also if a non-linear relationship exists between these factors and race performance. Secondly, an additional possible limitation of correlating MUM performance with body fat percentage could be the confounding variable of training as mentioned above (Legaz and Eston 2005). The underlying principle being that if a similar energy intake was assumed that those athletes with the highest volume of training would metabolise the most body fat and on average have the lowest body fat percentage, but also affect physiological variables such as  $VO_{2MAX}$ . To address the effect of training specifically versus anthropometric variables a future study could collect both anthropometric and specifically training data, after which an attempt could be made to predict performance with anthropometric variables while controlling for effects of training. Chapter 4 of this thesis addresses the confounding effects that training might have on both anthropometric variables and physiological variables by performing a pooled analysis of the data collected in this and the previous chapter. Finally, future studies could address a noted limitation of our current study which is that two of the three years had a relatively low heat stress. Therefore, a future study investigating MUM performance with similar anthropometric variables, but in a hot and humid environment, would be ideal.

### **3.5. Conclusion**

The results did not support the hypothesis that for runners that have a high aerobic capacity a greater lower-limb girth would be associated with a faster finishing time, as well as faster times during the uphill portions of the race. The second hypothesis that surface-area-to-body-mass ratio would be negatively associated with finishing time was partially supported by our current results with a negative association with finishing time and mass-adjusted surface area. The third hypothesis was supported with a lower endomorphy being associated with finishing time and predicting one of the three hill climb times. Finally, the fourth hypothesis was supported with a lower body fat percentage consistently predicting faster finishing and hill climb times.

### 3.6. Chapter 3 Data

**Table 3.1** Participants anthropometric characteristics and age, n=34.

Variable	Mean (SD)
Endomorphy	3.1 (0.8)
Mesomorphy	4.4 (1.1)
Ectomorphy	2.9 (1.2)
Body Fat Percentage (%)	20.7 (4.6)
Height (m)	1.8 (0.1)
Body Mass (kg)	70.8 (9.7)
Body Mass Index (kg•m <sup>-2</sup> )	22.4 (2.4)
Age (y)	46.5 (9.3)
Body Surface Area (m <sup>2</sup> )	1.8 (0.2)
Surface-area-to-body-mass Ratio (m <sup>2</sup> •kg <sup>-1</sup> )	1.20 (0.08) x 10 <sup>-2</sup>

**Table 3.2** Effect sizes for main predictor variables

Predictor Variable for Race Finishing Time	Hypothesized Effect Size (% variance explained)	Data Employed for Justification	Sample Size Required For Detection
Lower-limb Circumference	34%	Miura et al. (2002) Found that CSA explained 34% of W' during a 90s all out cycling test.	32
Surface-area-to-body-mass Ratio	40%	Marino et al. (2000) Found that a surface-area-to-body-mass ratio explained 17-59% of heat storage.	26

All calculations were done using G\*Power 3.1 Software using correlational bivariate normal model setting. The following input criteria are as follows: Tails = two, correlation to reject null hypothesis = hypothesized effect size, alpha error probability = 0.05, power = 0.80, correlation of null hypothesis = 0.

**Table 3.3** Equations for the calculation

Equation Formula	Equation Number
$\text{Endomorphy} = -0.7182 + 0.1451(X) - 0.00068(X^2) + 0.0000014(X^3)$	Equation 3.1
$\text{Mesomorphy} = 0.858(\text{Humerus Breadth}) + 0.601(\text{Femur Breadth}) + 0.188(\text{Corrected Arm Girth}) \\ + 0.161(\text{Corrected Calf Girth}) - 0.131(\text{Height}) + 4.5$	Equation 3.2
$\text{If Height Weight Ratio (HWR) is } \geq \text{ to } 40.75 \text{ then ectomorphy} = 0.732 \text{ HWR} - 28.58$	Equation 3.3
$\text{If HWR} < 40.75 \text{ but } > 38.25 \text{ then ectomorphy} = 0.463 \text{ HWR} - 17.63$	Equation 3.4
$\text{If HWR} < 38.25 \text{ then ectomorphy} = 0.1$	Equation 3.5
$\text{Estimated Body Surface Area} = 71.84(\text{Height})^{0.725} \times \text{Weight}^{0.425}$	Equation 3.6
$\text{BF\% Male} = 20.94878 + 0.1166(\text{Age}) - 0.11666(\text{Height}) + 0.42696(\text{Sum of 4 Skinfolts})$	Equation 3.7
$\text{BF\% Female} = 22.18945 + 0.06368(\text{Age}) + 0.60404(\text{BMI}) - 0.1452(\text{Height}) + 0.30919(\text{Sum of 4 Skinfolts}) \\ - 0.00099562(\text{Sum of 4 Skinfolts})^2$	Equation 3.8

All equations were taken directly from their respective sources. Heath-Carter Somatotype Equations 3.1-3.5 (Carter 2002), Estimated Body Surface Area Equation 3.6 (Du Bois and Du Bois 1989), Body Fat Percentage Equations 3.7 and 3.8 (Peterson, Czerwinski, and Siervogel 2003). X = (sum of triceps, subscapular and supraspinale skinfolts) x 170.18 / Height. All breath, girth and height measures are in cm, weight was measured in kg. HWR = Height-Weight Ratio.

**Table 3.4** Pearson correlation matrix of anthropometric variables and finishing time; \*p<0.05, \*\*p<0.01, n=34.

	Finish- ing Time	Endo- omorphy	Meso- omorphy	Ecto- omorphy	Thigh Girth	Calf Girth	Body fat percentage	Surface Area	$A_{DM}^{-1}$	Body Mass	Body Mass Index	MA Surface Area (m <sup>2</sup> )
Finishing Time (min)	1.00	-	-	-	-	-	-	-	-	-	-	-
Endomorphy	0.51**	1.00	-	-	-	-	-	-	-	-	-	-
Mesomorphy	0.13	0.03	1.00	-	-	-	-	-	-	-	-	-
Ectomorphy	-0.42*	-0.44**	-0.72**	1.00	-	-	-	-	-	-	-	-
Thigh Girth (cm)	0.13	0.40*	0.26	-0.54**	1.00	-	-	-	-	-	-	-
Calf Girth (cm)	0.16	0.18	0.56**	-0.53**	0.58**	1.00	-	-	-	-	-	-
Body fat percentage (%)	0.59*	0.78**	0.08	-0.44**	0.34	0.18	1.00	-	-	-	-	-
Surface Area (m <sup>2</sup> )	0.06	0.23	0.18	-0.24	0.45**	0.58**	-0.02	1.00	-	-	-	-
$A_{DM}^{-1}$ (m <sup>2</sup> •kg <sup>-1</sup> )	-0.32	-0.44**	-0.58**	0.79**	-0.62**	-0.71**	-0.29	-0.79**	1.00	-	-	-
Body Mass (kg)	0.19	0.33	0.37*	-0.51**	0.55**	0.67**	0.10	0.95**	-0.92**	1.00	-	-
Body Mass Index (kg•m <sup>-2</sup> )	0.37*	0.43*	0.68**	-0.92**	0.63**	0.69**	0.34*	0.59**	-0.96**	0.80**	1.00	-
MA Surface Area (m <sup>2</sup> )	-0.35*	-0.64**	0.84**	-0.25	-0.20	-0.38*	0.29	0.35*	-0.01	-0.53**	0.76**	1.00

MA = mass-adjusted

**Table 3.5** Pearson correlation matrix of anthropometric variables and hill 1 climb time; \* $p < 0.05$ , \*\* $p < 0.01$ ,  $n = 28$ .

	Hill 1 Climb Time	Endo- morphy	Meso- morphy	Ecto- morphy	Thigh Girth	Calf Girth	Body fat percentage	Surface Area	$A_{DM}^{-1}$	Body Mass	Body Mass Index	MA Surface Area (m <sup>2</sup> )
Hill 1 Climb Time (min)	1.00	-	-	-	-	-	-	-	-	-	-	-
Endomorphy	0.56**	1.00	-	-	-	-	-	-	-	-	-	-
Mesomorphy	0.07	0.03	1.00	-	-	-	-	-	-	-	-	-
Ectomorphy	-0.46*	-0.44**	-0.72**	1.00	-	-	-	-	-	-	-	-
Thigh Girth (cm)	0.35	0.40*	0.26	-0.54**	1.00	-	-	-	-	-	-	-
Calf Girth (cm)	0.20	0.18	0.56**	-0.53**	0.58**	1.00	-	-	-	-	-	-
Body fat percentage (%)	0.62**	0.78**	0.08	-0.44**	0.34	0.18	1.00	-	-	-	-	-
Surface Area (m <sup>2</sup> )	0.00	0.23	0.18	-0.24	0.45**	0.58**	-0.02	1.00	-	-	-	-
$A_{DM}^{-1}$ (m <sup>2</sup> •kg <sup>-1</sup> )	-0.30	-0.44**	-0.58**	0.79**	-0.62**	-0.71**	-0.29	-0.79**	1.00	-	-	-
Body Mass (kg)	0.14	0.33	0.37*	-0.51**	0.55**	0.67**	0.10	0.95**	-0.92**	1.00	-	-
Body Mass Index (kg•m <sup>-2</sup> )	0.37	0.43*	0.68**	-0.92**	0.63**	0.69**	0.34*	0.59**	-0.96**	0.80**	1.00	-
MA Surface Area (m <sup>2</sup> )	-0.37	-0.64**	0.84**	-0.25	-0.20	-0.38*	0.29	0.35*	-0.01	-0.53**	0.76**	1.00

MA = mass-adjusted

**Table 3.6** Pearson correlation matrix of anthropometric variables and hill 2 climb time; \* $p < 0.05$ , \*\* $p < 0.01$ ,  $n = 28$ .

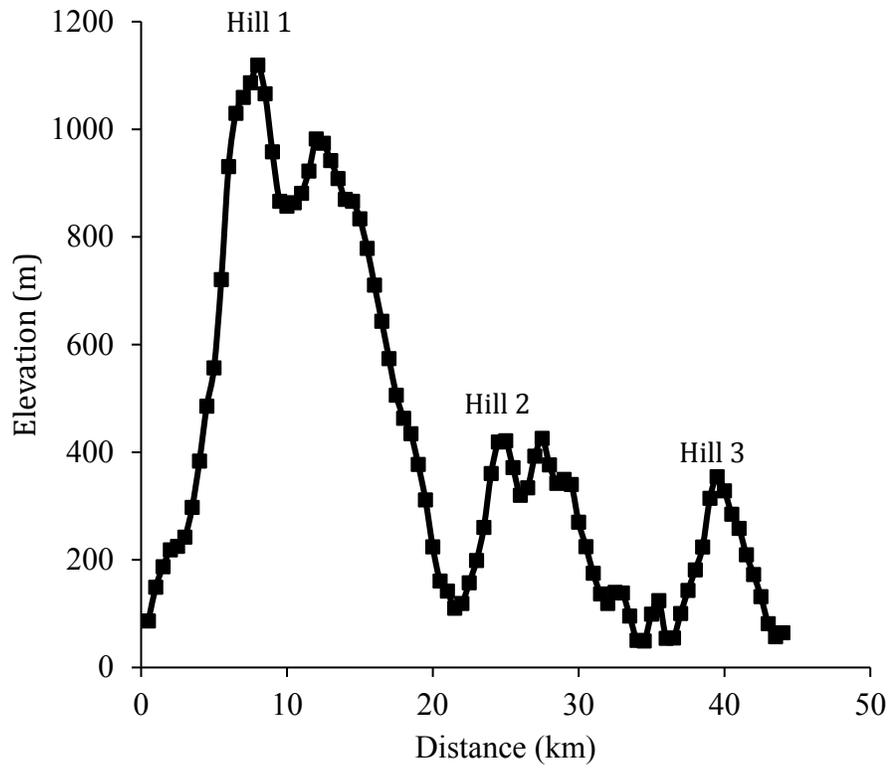
	Hill 2 Climb Time	Endo- morphy	Meso- morphy	Ecto- morphy	Thigh Girth	Calf Girth	Body fat percentage	Surfac e Area	$A_{DM}^{-1}$	Body Mass	Body Mass Index	MA Surface Area ( $m^2$ )
Hill 2 Climb Time (min)	1.00	-	-	-	-	-	-	-	-	-	-	-
Endomorphy	0.38*	1.00	-	-	-	-	-	-	-	-	-	-
Mesomorphy	0.01	0.03	1.00	-	-	-	-	-	-	-	-	-
Ectomorphy	-0.19	-0.44**	-0.72**	1.00	-	-	-	-	-	-	-	-
Thigh Girth (cm)	-0.10	0.40*	0.26	-0.54**	1.00	-	-	-	-	-	-	-
Calf Girth (cm)	-0.09	0.18	0.56**	-0.53**	0.58**	1.00	-	-	-	-	-	-
Body fat percentage (%)	0.15	0.78**	0.08	-0.44**	0.34	0.18	1.00	-	-	-	-	-
Surface Area ( $m^2$ )	0.14	0.23	0.18	-0.24	0.45**	0.58**	-0.02	1.00	-	-	-	-
$A_{DM}^{-1}$ ( $m^2 \cdot kg^{-1}$ )	-0.21	-0.44**	-0.58**	0.79**	-0.62**	-0.71**	-0.29	-0.79**	1.00	-	-	-
Body Mass (kg)	0.22	0.33	0.37*	-0.51**	0.55**	0.67**	0.10	0.95**	-0.92**	1.00	-	-
Body Mass Index ( $kg \cdot m^{-2}$ )	0.23	0.43*	0.68**	-0.92**	0.63**	0.69**	0.34*	0.59**	-0.96**	0.80**	1.00	-
MA Surface Area ( $m^2$ )	-0.23	-0.64**	0.84**	-0.25	-0.20	-0.38*	0.29	0.35*	-0.01	-0.53**	0.76**	1.00

MA = mass-adjusted

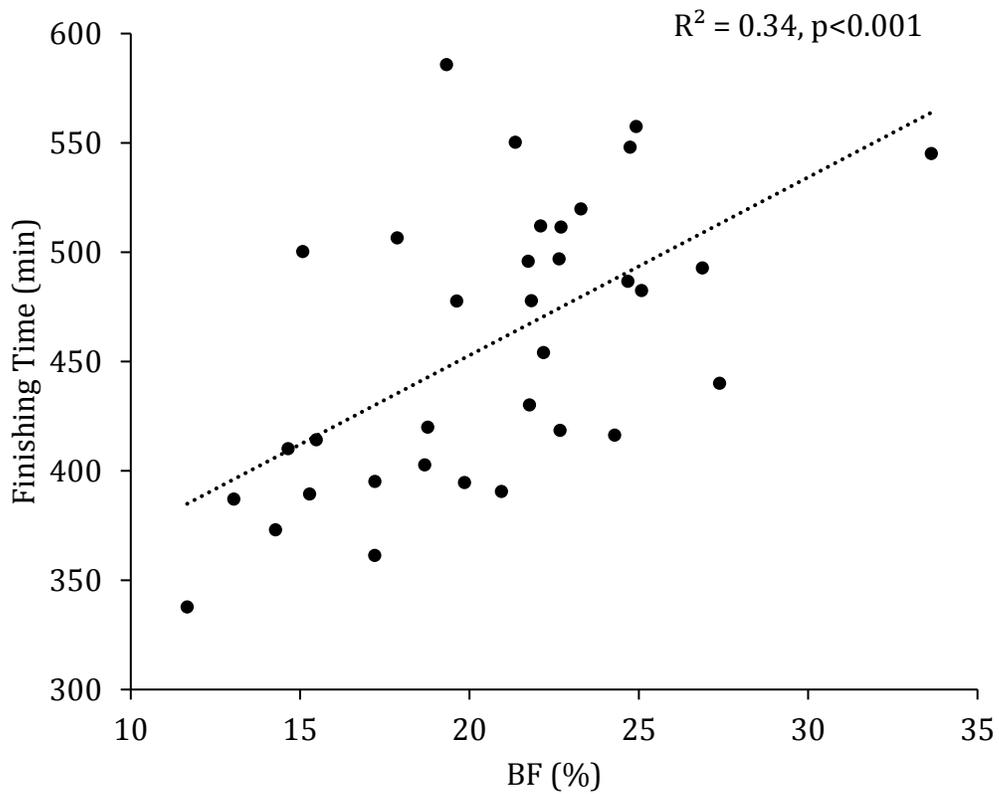
**Table 3.7** Pearson correlation matrix of anthropometric variables and hill 3 climb time; \*p<0.05, \*\*p<0.01, n=28.

	Hill 3 Climb Time	Endo- morphism	Meso- morphism	Ecto- morphism	Thigh Girth	Calf Girth	Body fat percentage	Surface Area	$A_{DM}^{-1}$	Body Mass	Body Mass Index	MA Surface Area (m <sup>2</sup> )
Hill 3 Climb Time (min)	1.00	-	-	-	-	-	-	-	-	-	-	-
Endomorphy	0.51**	1.00	-	-	-	-	-	-	-	-	-	-
Mesomorphy	0.05	0.03	1.00	-	-	-	-	-	-	-	-	-
Ectomorphy	-0.33	-0.44**	-0.72**	1.00	-	-	-	-	-	-	-	-
Thigh Girth (cm)	0.17	0.40*	0.26	-0.54**	1.00	-	-	-	-	-	-	-
Calf Girth (cm)	0.19	0.18	0.56**	-0.53**	0.58**	1.00	-	-	-	-	-	-
Body fat percentage (%)	0.63**	0.78**	0.08	-0.44**	0.34	0.18	1.00	-	-	-	-	-
Surface Area (m <sup>2</sup> )	0.16	0.23	0.18	-0.24	0.45**	0.58**	-0.02	1.00	-	-	-	-
$A_{DM}^{-1}$ (m <sup>2</sup> •kg <sup>-1</sup> )	-0.32	-0.44**	-0.58**	0.79**	-0.62**	-0.71**	-0.29	-0.79**	1.00	-	-	-
Body Mass (kg)	0.25	0.33	0.37*	-0.51**	0.55**	0.67**	0.10	0.95**	-0.92**	1.00	-	-
Body Mass Index (kg•m <sup>-2</sup> )	0.34	0.43*	0.68**	-0.92**	0.63**	0.69**	0.34*	0.59**	-0.96**	0.80**	1.00	-
MA Surface Area (m <sup>2</sup> )	-0.24	-0.64**	0.84**	-0.25	-0.20	-0.38*	0.29	0.35*	-0.01	-0.53**	0.76**	1.00

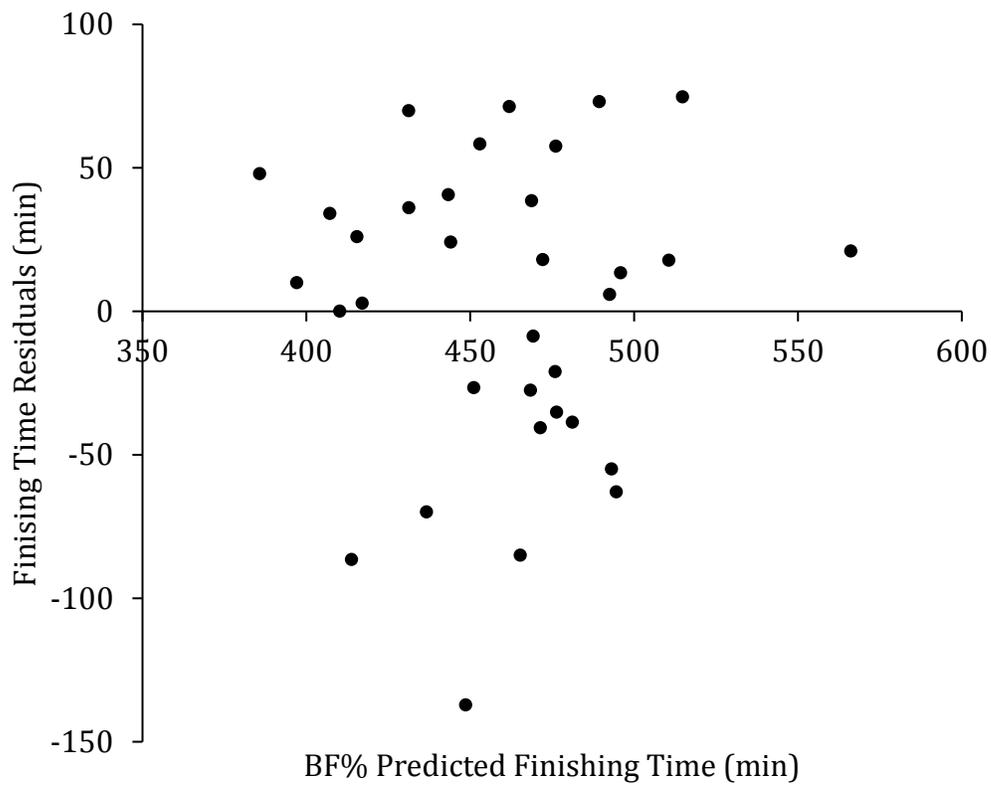
MA = mass-adjusted



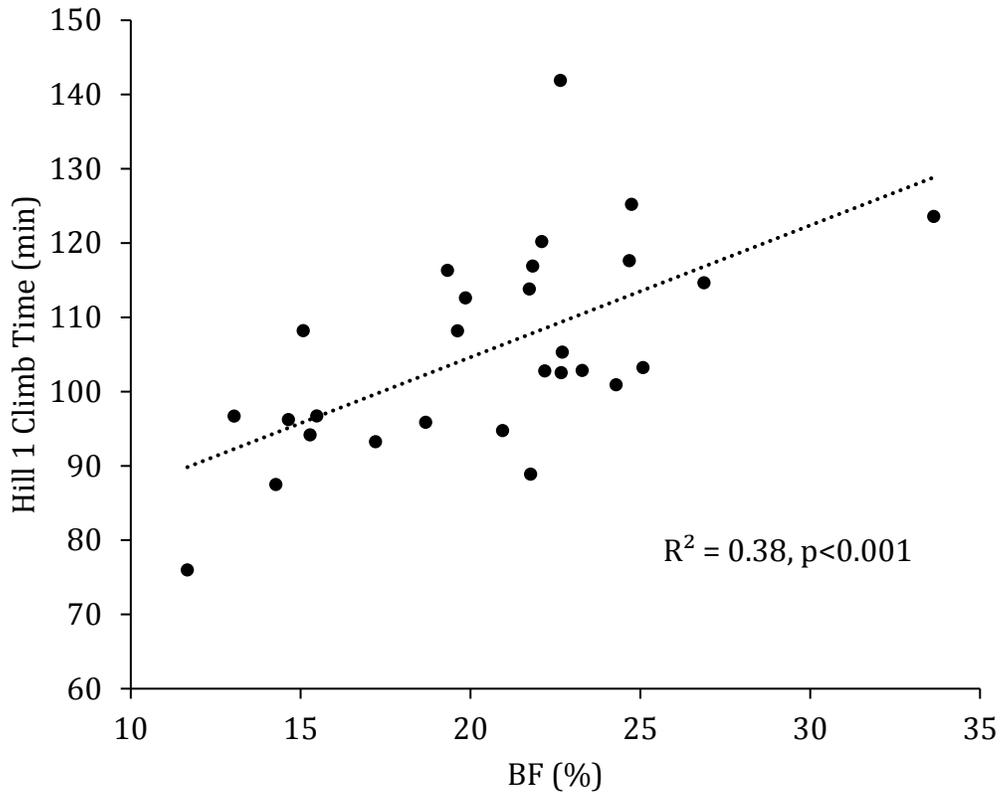
**Figure 3.1** Race course elevation profile. Hill 1 = Black Mountain, hill 2 = Grouse Mountain, hill 3 = Seymour Grind.



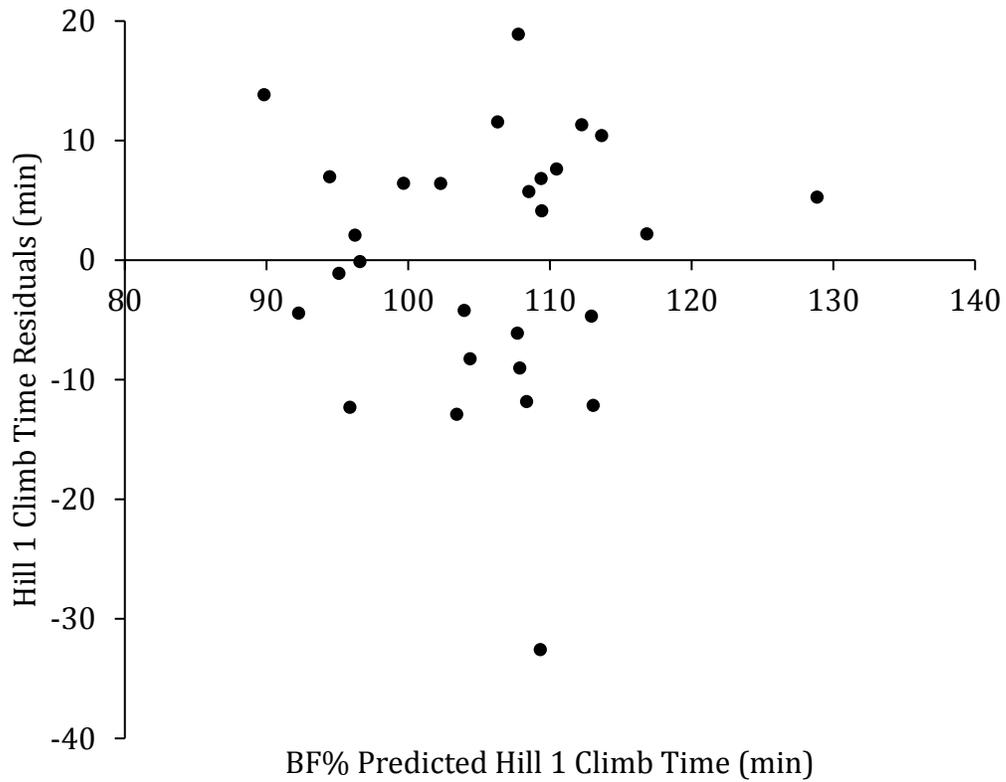
**Figure 3.2** First order linear regression of finishing time as a function of body fat percentage (BF%),  $n=34$ ,  $p < 0.001$ . Regression line equation: finishing time =  $8.1 \cdot \text{BF}(\%) + 290.0$ .



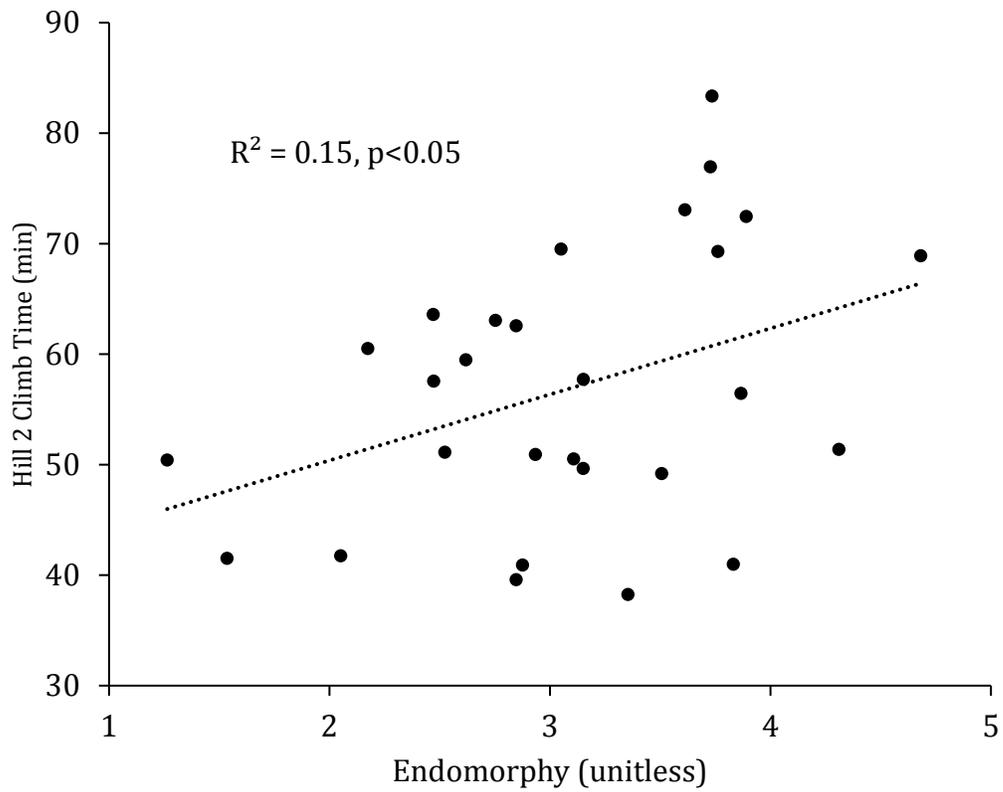
**Figure 3.3** Residuals of finishing time over the range of predicted finishing times by the first order regression of BF%. Finishing time residuals = BF% predicted finishing time – actual finishing time. n=34, Shapiro-Wilk’s analysis (p=0.17).



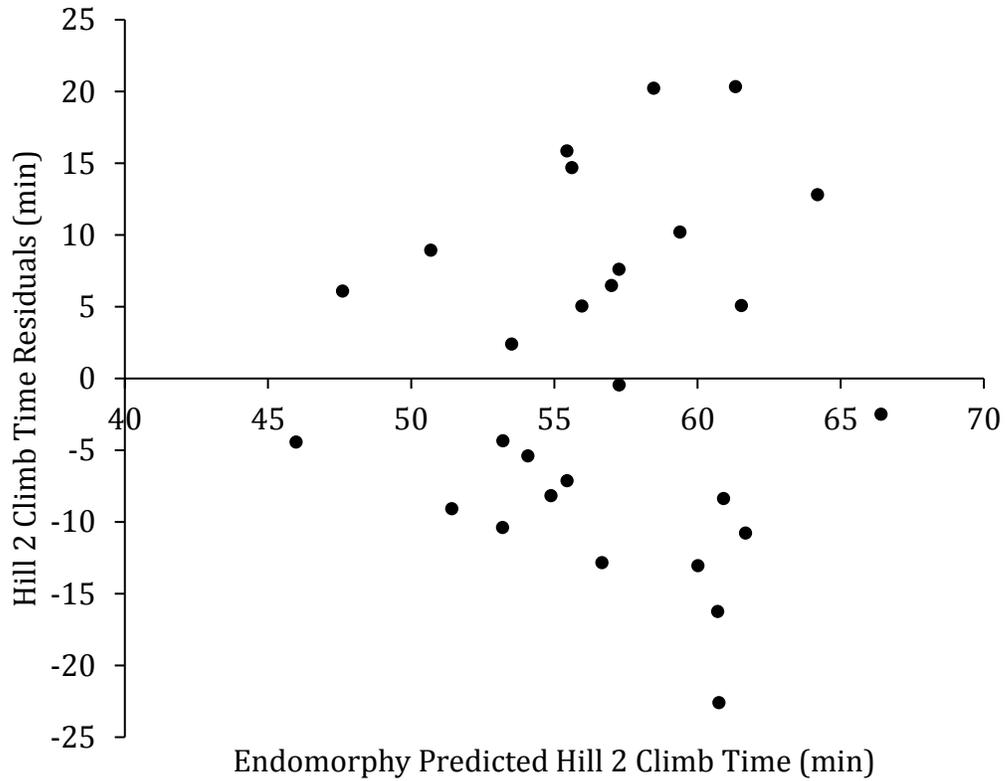
**Figure 3.4** First order linear regression of hill 1 climb time as a function of body fat percentage (BF%),  $n=34$ ,  $p<0.001$ . Regression line equation: hill 1 climb time (min) =  $1.8 \cdot \text{BF}(\%) + 69.1$ .



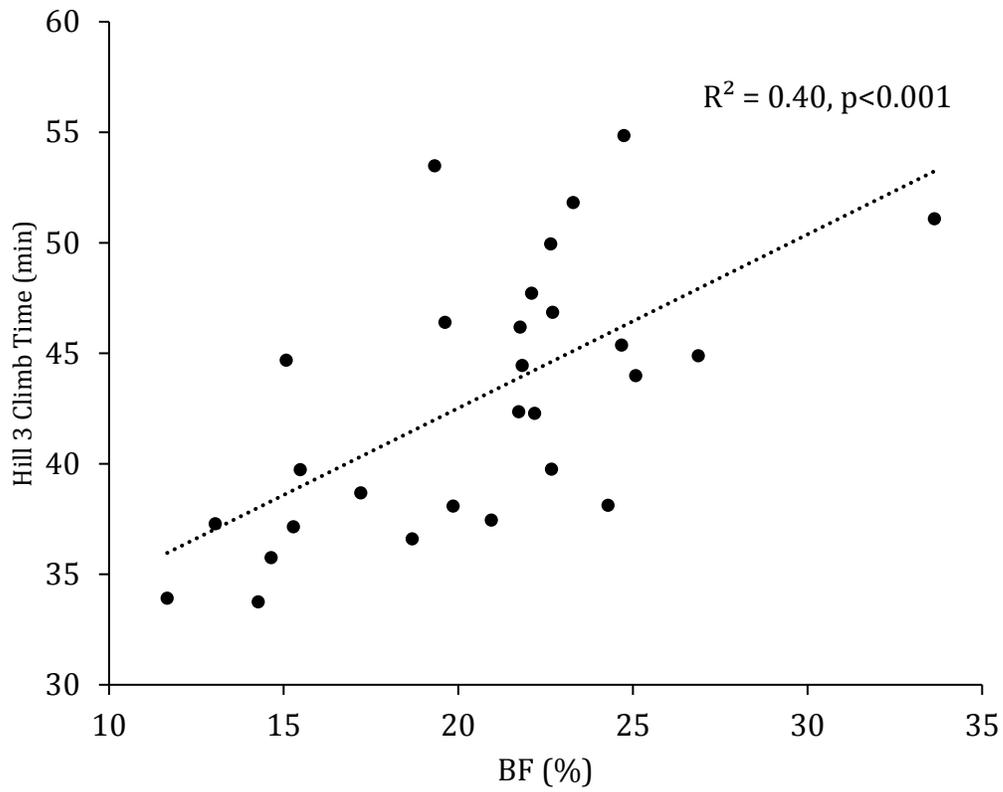
**Figure 3.5** Residuals of hill 1 climb time over the range of predicted hill 1 climb time by the first order regression of BF%. Hill 1 climb time Residuals = BF% predicted hill 1 climb time – actual hill 1 climb time. n=28, Shapiro-Wilk's analysis (p=0.13).



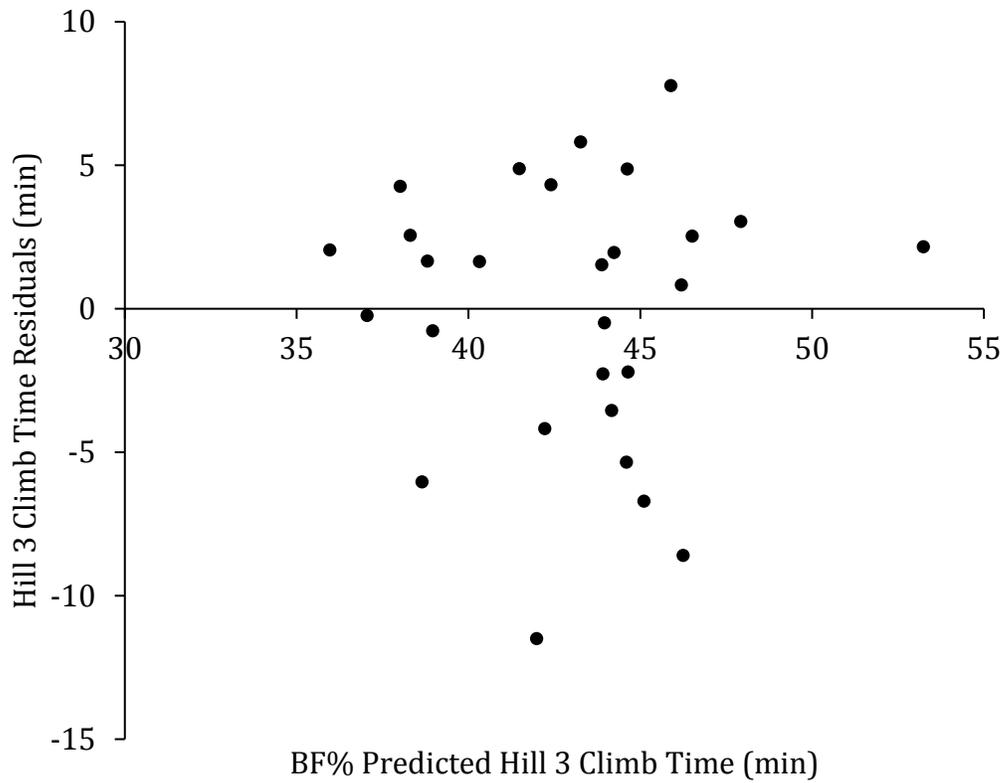
**Figure 3.6** First order linear regression of hill 2 climb time as a function of endomorphy,  $n=34$ ,  $p < 0.05$ . Regression line equation: hill 1 climb time (min) =  $6.0 \cdot \text{endomorphy} + 28.4$ .



**Figure 3.7** Residuals of hill 2 climb time over the range of predicted hill 2 climb time by the first order regression of endomorphy. Hill 2 climb time residuals = endomorphy predicted hill 2 climb time – actual hill 2 climb time. n=28, Shapiro-Wilk’s analysis (p=0.63).



**Figure 3.8** First order linear regression of hill 3 climb time as a function of body fat percentage (BF%), n=34, p <0.001. Regression line equation: hill 1 climb time (min) = 0.79•BF(%) + 26.8.



**Figure 3.9** Residuals of hill 3 climb time over the range of predicted hill 3 climb time by the first order regression of BF%. Hill 3 climb time residuals = BF% predicted hill 3 climb time – actual hill 3 climb time. n=28, Shapiro-Wilk's analysis (p=0.22).

## Chapter 4.

# Prediction of mountain ultra marathon performance with anthropometric and physiological variables

### 4.1. Introduction

As described in Chapters 2 and 3, there are several physiological and anthropometric variables including somatotypes that have been associated with MUM race performance including, amongst others, critical velocity, anaerobic capacity and surface-area-to-body-mass ratio. These variables, however, cannot be assumed to independently affect race to MUM finishing and hill climb times in isolation since there are several independent variables predictors that are collinear. For example, a larger lower-limb girth has been shown to correlate to a greater anaerobic work capacity (Miura et al. 2002), possibly due to increased stores of ATP and PCr. Surface-area-to-body-mass ratio ( $A_{DM}^{-1}$ ) might also correlate to critical velocity since a greater  $A_{DM}^{-1}$  gives a greater area per kilogram of body mass so as to allow a more effective sweat evaporation that helps to maintain a lower core temperature (Havenith, Luttikholt, and Vrijlkotte 1995). Since a higher core temperature can suppress maximal aerobic capacity ( $\dot{V}O_{2MAX}$ ) (Nybo et al. 2001) and consequently critical velocity (Jones et al. 2010), then hyperthermia stands to potentially reduce running velocity during the race.

The purpose of this chapter was to run a subsequent set of stepwise univariate multiple linear regression analyses to assess how the combination of physiological predictor variables from the Chapter 2 study and anthropometric predictor variables from the Chapter 3 study influence MUM finishing time. It was hypothesized that through multiple linear regression of physiological and anthropometric variables that a combination of these measures would significantly add to the explanation of variance in finishing time and hill climb times compared to the same assessment with physiological variables in isolation and anthropometric variables in isolation.

## 4.2. Methods

### 4.2.1. Participants, Instrumentation, and Protocol

The sample recruited for this chapter is identical to that used in Chapters 2 and 3. For their anthropometric and physiological characteristics, please refer to Sections 2.1 and 3.1. For this chapter the number of participants was limited to those which had completed both the entirety of the anthropometric and physiological testing, specifically the 12 participants, 11 males and one female, which had completed the CV testing subset in Chapter 2. Each participant received an orientation of the laboratory and a 24-h reflection period, after which each participant was required to complete a PAR-Q and sign an informed consent form. The SFU Office of Research Ethics approved this study.

A sample size justification calculation was conducted for multiple univariate linear regression using the estimated percent of finishing time variance explained by each variable, as described in Sections 2.2.2 and 3.2.2, and assuming a medium covariance to each other ( $R^2=0.15$ ). With an alpha of 0.05 and a power of 80%, 12 participants were determined to be required to show a prediction of finishing time using multiple univariate linear regression.

No additional instrumentation or protocols were run for this chapter. Please refer to Sections 2.2.2. and 2.2.3 for the description of the physiological variable methods, and Sections 3.2.2. and 3.2.3. for the description of anthropometric methods. For this chapter only data from the third year of testing, 2016, was used as this was the only year which a complete data set was present for multiple regression analysis. The race conditions of this year was heavy rainfall with DBT of ~14-20°C and ~100% RH.

### 4.2.2. Statistical Analysis

Multiple univariate stepwise linear regression analyses were employed to assess the relationship between the dependent variables of race finishing time and hill climb times and each of the physiological and anthropometric variables. Anthropometric variables included body mass, body mass index (BMI), lower-limb girths, somatotypes, body fat percentage (BF%), surface area ( $A_D$ ), surface-area-to-body-mass ratio ( $A_D \cdot m^{-1}$ ). Physiological variables included critical velocity (CV),  $D'$ , aerobic power ( $\dot{V}O_{2\text{MAX}}$ ),

Wingate anaerobic test peak power (WAnT PP), Wingate anaerobic test mean power (WAnT MP) and the rate of oxygen consumption at the gas exchange threshold as determined by the V-slope method ( $\dot{V}O_{2VSLOPE}$ ). The volume of Oxygen consumption at first lactate threshold was determined by inflection point of ( $\dot{V}O_{2MAX}$ ) versus Log (lactate) ( $\dot{V}O_{2LL}$ ) as described previously (Beaver, Wasserman, and Whipp 1985). The exercise intensity at  $\dot{V}O_{2VSLOPE}$  and  $\dot{V}O_{2LL}$  was also determined as the stage, where a stage is described by its velocity and its grade at which these thresholds occurred ( $\dot{V}O_{2VSLOPE}$  Stage and  $\dot{V}O_{2LL}$  Stage) as described in section 2.2.3. The size-dependent variables of  $\dot{V}O_{2MAX}$  ( $L \cdot \text{min}^{-1}$ ), WAnT PP (W), WAnT MP (W),  $\dot{V}O_{2VSLOPE}$  ( $L \cdot \text{min}^{-1}$ ),  $\dot{V}O_{2LL}$  ( $L \cdot \text{min}^{-1}$ ), and surface area were all regressed against body mass and the residuals of each variable were employed in the analyses as mass-adjusted values. The final overall finishing time equation was validated with a leave-one-out cross-validation (Kohavi 1995). This validation was completed by 12 iterations. Each iteration was performed by removing one participant from the data set and predicting their finishing time. These predicted finishing times were then regressed against actual finishing times.

## 4.3. Results

### 4.3.1. Prediction of Overall Race Time

Stepwise multiple univariate linear regression with the input of all physiological and anthropometric variables resulted in the prediction of race performance with the input of CV and endomorphy (Table 4.1) explaining 88% of the variance ( $p < 0.001$ ) of finishing time (Equation 4.1):

$$\text{finishing time (min)} = -92.2 \cdot \text{CV (m} \cdot \text{s}^{-1}) + 40.8 \cdot \text{endomorphy (unitless)} + 639.4 \text{ (min)}$$

.....Equation 4.1

The cross-validation of this equation, using the method described by Kohavi, showed a significant relationship ( $p < 0.001$ ) of predicted and actual overall race finishing time (Fig. 4.1), accounting for 85% of the total variance. Each iteration of this validation is shown in Table 4.2. Inspection of this table indicated a consistency of the regression coefficient values and coefficient of determination, throughout the 12 iterations of the

model. Homoscedasticity and a normal distribution were observed in the residuals (Figure 4.2).

### 4.3.2. Prediction of Hill Climb Times

For hill 1, climb time was predicted with the input BF% and CV (Table 4.3). For hill 1, BF% and CV explained a total of 96% of the variance in hill 1 climb time (Equation 4.2):

$$\text{hill 1 climb time (min)} = -16.3 \cdot \text{CV (m} \cdot \text{s}^{-1}) + 1.3 \cdot \text{BF (\%)} + 136.1 \dots \dots \dots \text{Equation 4.2}$$

In stepwise multiple univariate linear regression analysis,  $\dot{V}O_{2LL}$  Stage was the sole predictor of hill 2 time (min) ( $R^2=0.68$ ,  $p=0.003$ ); the slope of  $-0.27$  (SEE  $0.07$ )  $\text{min} \cdot \text{m}^{-1} \cdot \text{s} \cdot \text{grade}^{-1}$  was found to be significantly different from zero ( $p=0.003$ ). Homoscedasticity and a normal distribution was observed in the residuals from a plot of hill 2 time as a function of  $\dot{V}O_{2LL}$  Stage as supported by the Shapiro-Wilk's analysis ( $p=0.14$ ) (Fig 2.6).

For hill 3, climb time was predicted with the input of CV, BF% and surface area (Table 4.4). These independent variables explained 97% of the variance of hill 3 climb time (Equation 4.3):

$$\text{hill 3 climb time (min)} = -9.2 \text{ CV (m} \cdot \text{s}^{-1}) + 0.6 \text{ BF (\%)} + 9.4 \text{ surface area (m}^2) + 45.7 \dots \dots \dots \text{Equation 4.3}$$

## 4.4. Discussion

The current results support that both overall finishing time and hill climb times are best predicted by a combination of physiological and anthropometric variables. The main novel finding of this analysis is that a combination of CV and endomorphy can be used to predict finishing time in this mountain ultra marathon race. Secondary findings are that anthropometric measures improved the explanation of variance of hill climb times, with both BF% and CV significantly contributing to the prediction of hill 1 time and CV, BF% and surface area significantly contributing to the prediction of hill 3 time.

Several of the variables entered in the multiple regression equations have been discussed in previous chapters of this thesis, including CV and BF% as shown in Chapters 2 and 3. Critical velocity theoretically represents the maximal aerobic pace of running (Jones et al. 2010, Hill and Ferguson 1999). Our current results extend the utility of CV as a metric for prediction of performance to ultra endurance events such as the mountain ultra marathon in this study. In mountainous terrain, the athletes with the greatest ability to maintain their movement without drawing upon D' and inducing fatigue are at a clear advantage (Hill and Ferguson 1999). Likewise, BF% is regarded as one of the most important anthropometric variables for the prediction of marathon and ultra marathon performance (Knechtle 2014). As discussed in Chapter 3, the prediction of hill 1 time might be explained by a lower BF% representing a lower energetic cost by the thinner runner who carries less excess body weight, which has been shown to reduce performance greatly (Cureton and Sparling 1980). The current results not only support that all of the above variables contribute to the prediction of MUM finishing time or hill climb times, but also that they add to the explanation of the variance independently as both were entered into the regression equation.

The current prediction of finishing time shows that CV explains 75% of the variance in finishing time, while endomorphy explains an additional 13% (Table 4.1). This two variable equation for the prediction MUM time is supported by the results of our cross-validation analysis (Kohavi 1995). Cross-validation analysis is one method to verify if a regression model from a given sample can be expected to accurately predict outcomes within the population. The current regression results suggest that our predictors of overall finishing time in the MUM race are applicable to the general race population. Visual inspection of the residuals (Figure 4.2) from this validation procedure supports a random distribution of the residuals and therefore supports that a linear model is a correct and adequate fit to the data over the range of the predicted values. Furthermore, looking at the individual iterations shows a consistency of the model as the removal of any single participant did not give a drastic change in the regression coefficient values or the coefficient of determination (Table 4.2). The ranges of coefficients of determination were from 0.82 to 0.90 for the MUM finishing time model. Overall, this evidence supports the use of this combination of variables in the prediction of MUM success and further research might seek to expand this application to other populations and events.

Our results for hill 3 climb time also showed that addition of surface area to the model resulted in a small 6% but significant increase in explanation of variation in hill climb time, indicating that as surface area increases climb time would become slower. This is an unexpected result as it would be expected that a greater surface area would be correlated to an improvement in performance as this would allow for greater surface area to facilitate evaporative heat loss (Marino et al. 2000). The rationale being that the facilitation of evaporative heat loss would be put these runners at a thermoregulatory advantage during an endurance race where hyperthermia is known to inhibit performance (González-Alonso et al. 1999).

A potential limitation of this study could be argued to be the relatively small samples size. However, our sample size is justified by the statistical power calculations made prior to the study, and our results are supported by the cross-validation analysis. In future studies, a more stringent external validation of this model could involve recruiting an entirely different population of runners and attempting to independently predict their race finishing times and hill climb times in a subsequent year of the Knee Knackering North Shore Trail Run race. Multicollinearity must also be considered in any study with many independent predictor variables that are being used to predict a dependant variable. This thesis mediated this potential issue in several ways. Firstly, by separately considering the physiological and anthropometric variables in Chapters 2 and 3 before applying a combined analysis here in Chapter 4. Secondly, by considering the results in the context of the current literature. In both of these considerations, the results in this Chapter appear consistent with what was observed in Chapters 2 and 3 and what has been observed in previous studies as described above.

With reference to race finishing time, our results do support and expand upon Coyle's model of endurance performance ability. The three main determinants of performance in Coyle's model can be summarized as the contributions of  $\dot{V}O_{2MAX}$ , the % of  $\dot{V}O_{2MAX}$  at lactate threshold, and running economy (Coyle 1995). Critical velocity theoretically combines all three of these components, while endomorphy and % body fat could be suggested to be related to the running economy as described above (Vernillo et al. 2013, Cureton and Sparling 1980). Indeed, our prediction of a faster race time with a lower endomorphy is well supported by previous studies of iron-distance athletes (Kandel, Baeyens, and Clarys 2014) and Kenyan marathon athletes (Vernillo et al.

2013). In both these studies, it was found that a higher ectomorphic and lower endomorphic body type was advantageous for running performance. On this basis, the current results fit well into the overall understanding of endurance performance and provide insight into how this understanding applies to MUMs.

### ***Future Directions***

The current study provides a theoretical prediction equation for the prediction of race time with critical velocity and endomorphy. Although we have cross validated this equation within the current data set as described above, a key future direction would be to validate this equation by predicting finishing times with independent data sets in the same and different MUM events. It is also important to understand if these predictor variables are as important within MUM events that are longer in distance, are multi-stage, or have markedly higher heat stress. Through such future studies the applicability and reliability of prediction of MUM events with physiological and anthropometric variables could continue to be better understood.

## **4.5. Conclusion**

Our results support the hypothesis for MUM runners with high aerobic power that through multiple linear regression of physiological and anthropometric variables including somatotype that a combination of these measures significantly adds to the explanation of variance in finishing time and hill climb times in a 50 km MUM race compared to the same assessment with physiological variables in isolation and anthropometric variables in isolation.

## 4.6. Chapter 4 Data

**Table 4.1** Stepwise multiple univariate linear regression of CV and endomorphy to finishing time. Variable values are unstandardized regression coefficients, n=12. CV = critical velocity.

Regression coefficients					
CV (m·s <sup>-1</sup> )	Endomorphy (unitless)	Intercept (min)	SE	R <sup>2</sup>	p
-129.1		898.7	36.6	0.75	<0.001
-92.2	40.8	639.4	26.1	0.88	<0.001

**Table 4.2** Validation analysis of prediction of MUM finishing time with critical velocity and endomorphy. Values are the unstandardized regression coefficients, n=11 for each iteration (Kohavi 1995).

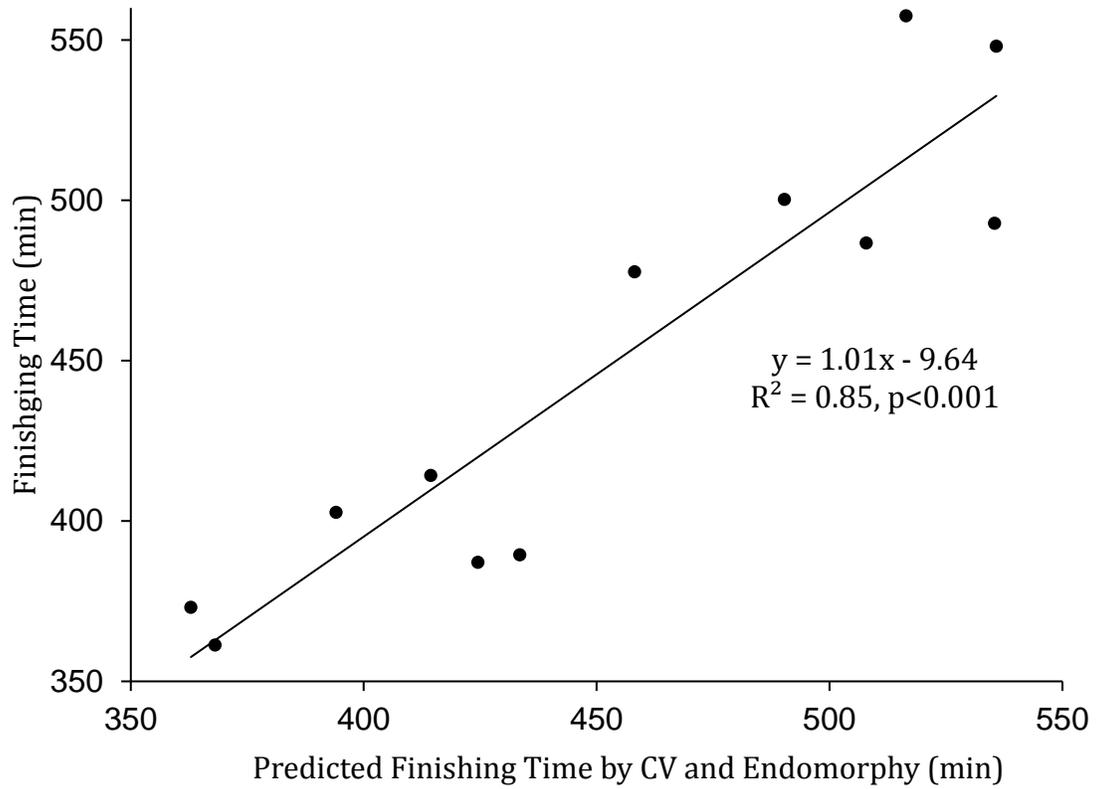
Iteration	Critical Velocity (m•s <sup>-1</sup> )	Endomorphy (unitless)	Intercept (min)	SE (min)	R <sup>2</sup>
1	-86.0	44.4	605.1	27.0	0.89
2	-87.9	41.2	622.2	23.8	0.86
3	-94.5	41.1	645.7	26.6	0.87
4	-104.5	29.2	723.5	36.0	0.90
5	-92.2	40.8	639.4	27.7	0.88
6	-88.0	36.8	634.3	24.5	0.88
7	-94.4	42.0	645.0	26.8	0.89
8	-79.4	55.2	552.5	25.9	0.89
9	-93.8	31.5	670.8	30.6	0.85
10	-92.6	32.5	665.6	31.2	0.82
11	-100.3	30.4	728.7	27.4	0.88
12	-88.9	34.4	649.6	27.6	0.88

**Table 4.3** Stepwise Multiple univariate linear regression of critical velocity and body fat percentage variables to hill 1 climb time. Variable values are unstandardized regression coefficients, n=12. CV = critical velocity, BF = body fat.

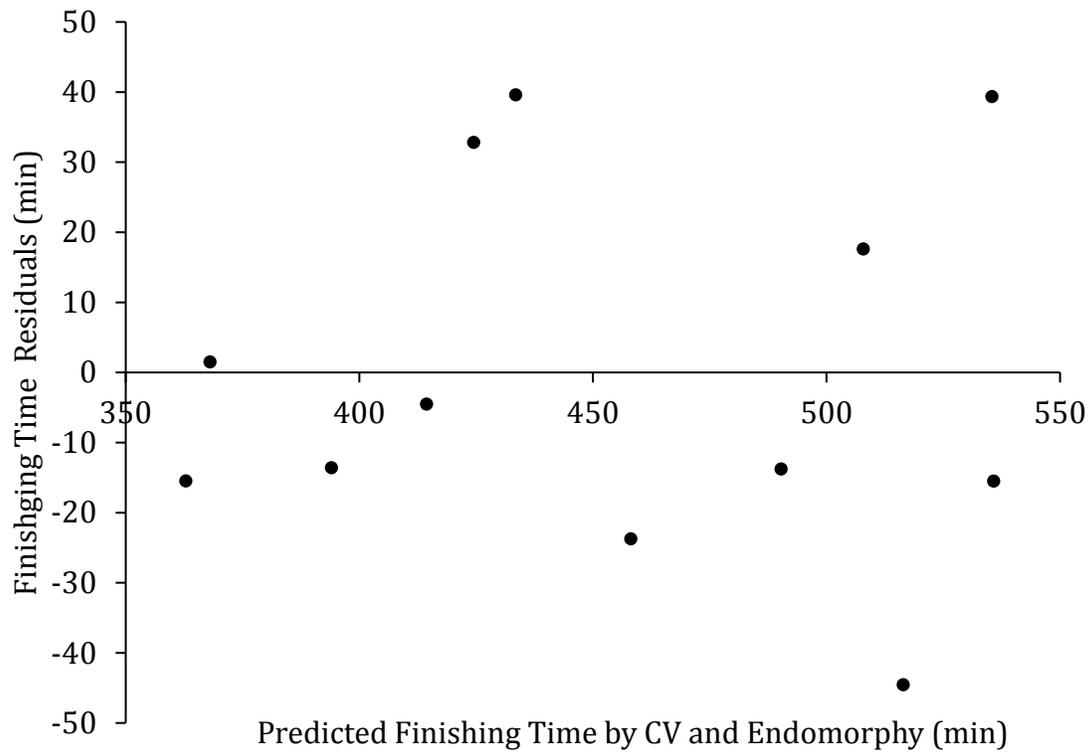
Regression coefficients					
CV (m•s <sup>-1</sup> )	BF% (%)	Intercept (min)	SE (min)	R <sup>2</sup>	p
-23.6		186.1	6.6	0.73	0.002
-16.3	-1.3	136.1	2.6	0.96	<0.001

**Table 4.4** Stepwise multiple univariate linear regression of hill 3 climb time and physiological and anthropometric variables. Variable values are unstandardized regression coefficients, n=12. CV = critical velocity, BF = body fat.

Regression coefficients							
CV (m•s <sup>-1</sup> )	BF% (%)	Surface (m <sup>2</sup> )	Area	Intercept (min)	SE	R <sup>2</sup>	p
-12.9				86.6	3.0	0.80	<0.001
-10.4	0.5			69.4	2.2	0.91	<0.001
-9.2	0.6	9.4		45.7	1.3	0.97	<0.001



**Figure 4.1** First order regression of finishing time as a function finishing time predicted by CV and endomorphy as determined by the leave-one-out validation analysis;  $n=12$ ,  $p<0.001$ .



**Figure 4.2** Residuals from a first order regression of finishing time as a function finishing time predicted by CV and endomorphy as calculated by the leave-one-out validation analysis, n=12.

## References

- Asmussen, Erling, and Ove Boje. 1945. "Body Temperature and Capacity for Work." *Acta Physiologica Scandinavica* 10 (1):1-22.
- Barandun, U., B. Knechtle, P. Knechtle, A. Klipstein, C. A. Rüst, T. Rosemann, and R. Lepers. 2012. "Running speed during training and percent body fat predict race time in recreational male marathoners." *Open Access J Sports Med* 3:51-8. doi: 10.2147/OAJSM.S33284.
- Bassett, D. R., and E. T. Howley. 2000. "Limiting factors for maximum oxygen uptake and determinants of endurance performance." *Med Sci Sports Exerc* 32 (1):70-84.
- Beaver, W. L., K. Wasserman, and B. J. Whipp. 1985. "Improved detection of lactate threshold during exercise using a log-log transformation." *J Appl Physiol (1985)* 59 (6):1936-40.
- Beaver, W. L., K. Wasserman, and B. J. Whipp. 1986. "A new method for detecting anaerobic threshold by gas exchange." *J Appl Physiol (1985)* 60 (6):2020-7.
- Beneke, R., C. Pollmann, I. Bleif, R. M. Leithäuser, and M. Hütler. 2002. "How anaerobic is the Wingate Anaerobic Test for humans?" *Eur J Appl Physiol* 87 (4-5):388-92. doi: 10.1007/s00421-002-0622-4.
- Bessman, S. P., and C. L. Carpenter. 1985. "The creatine-creatine phosphate energy shuttle." *Annu Rev Biochem* 54:831-62. doi: 10.1146/annurev.bi.54.070185.004151.
- Billat, V. L., P. Sirvent, G. Py, J. P. Koralsztein, and J. Mercier. 2003. "The concept of maximal lactate steady state: a bridge between biochemistry, physiology and sport science." *Sports Med* 33 (6):407-26.
- Binder, R. K., M. Wonisch, U. Corra, A. Cohen-Solal, L. Vanhees, H. Saner, and J. P. Schmid. 2008. "Methodological approach to the first and second lactate threshold in incremental cardiopulmonary exercise testing." *Eur J Cardiovasc Prev Rehabil* 15 (6):726-34. doi: 10.1097/HJR.0b013e328304fed4.
- Brooks, G. A., and J. Mercier. 1994. "Balance of carbohydrate and lipid utilization during exercise: the "crossover" concept." *J Appl Physiol (1985)* 76 (6):2253-61.
- Buck, D., and L. McNaughton. 1999. "Maximal accumulated oxygen deficit must be calculated using 10-min time periods." *Med Sci Sports Exerc* 31 (9):1346-9.

- Bulbulian, R., A. R. Wilcox, and B. L. Darabos. 1986. "Anaerobic contribution to distance running performance of trained cross-country athletes." *Med Sci Sports Exerc* 18 (1):107-13.
- Burnley, M., J. H. Doust, and A. Vanhatalo. 2006. "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.
- Burtscher, M., H. Förster, and J. Burtscher. 2008. "Superior endurance performance in aging mountain runners." *Gerontology* 54 (5):268-71. doi: 10.1159/000148649.
- Cairns, S. P., W. A. Hing, J. R. Slack, R. G. Mills, and D. S. Loiselle. 1997. "Different effects of raised [K<sup>+</sup>]<sub>o</sub> on membrane potential and contraction in mouse fast- and slow-twitch muscle." *Am J Physiol* 273 (2 Pt 1):C598-611.
- Calbet, J. A., J. A. De Paz, N. Garatachea, S. Cabeza de Vaca, and J. Chavarren. 2003. "Anaerobic energy provision does not limit Wingate exercise performance in endurance-trained cyclists." *J Appl Physiol (1985)* 94 (2):668-76. doi: 10.1152/jappphysiol.00128.2002.
- Carter, J. E. L. 2002. *The Heath-Carter Anthropometric Somatotype*. Rev. ed. San Diego, Calif.
- Chaouachi, M., A. Chaouachi, K. Chamari, M. Chtara, Y. Feki, M. Amri, and F. Trudeau. 2005. "Effects of dominant somatotype on aerobic capacity trainability." *Br J Sports Med* 39 (12):954-9. doi: 10.1136/bjsm.2005.019943.
- Chidnok, W., J. Fulford, S. J. Bailey, F. J. Dimenna, P. F. Skiba, A. Vanhatalo, and A. M. Jones. 2013. "Muscle metabolic determinants of exercise tolerance following exhaustion: relationship to the "critical power"." *J Appl Physiol (1985)* 115 (2):243-50. doi: 10.1152/jappphysiol.00334.2013.
- Coyle, E. F. 1995. "Integration of the physiological factors determining endurance performance ability." *Exerc Sport Sci Rev* 23:25-63.
- Coyle, E. F., W. H. Martin, A. A. Ehsani, J. M. Hagberg, S. A. Bloomfield, D. R. Sinacore, and J. O. Holloszy. 1983. "Blood lactate threshold in some well-trained ischemic heart disease patients." *J Appl Physiol Respir Environ Exerc Physiol* 54 (1):18-23.
- Cureton, K. J., and P. B. Sparling. 1980. "Distance running performance and metabolic responses to running in men and women with excess weight experimentally equated." *Med Sci Sports Exerc* 12 (4):288-94.
- Davison, R. C., D. Swan, D. Coleman, and S. Bird. 2000. "Correlates of simulated hill climb cycling performance." *J Sports Sci* 18 (2):105-10. doi: 10.1080/026404100365171.

- Day, J. R., H. B. Rossiter, E. M. Coats, A. Skasick, and B. J. Whipp. 2003. "The maximally attainable VO<sub>2</sub> during exercise in humans: the peak vs. maximum issue." *J Appl Physiol* (1985) 95 (5):1901-7. doi: 10.1152/jappphysiol.00024.2003.
- Dekerle, J., G. Brickley, A. J. Hammond, J. S. Pringle, and H. Carter. 2006. "Validity of the two-parameter model in estimating the anaerobic work capacity." *Eur J Appl Physiol* 96 (3):257-64. doi: 10.1007/s00421-005-0074-8.
- Dempsey, J. A., P. G. Hanson, and K. S. Henderson. 1984. "Exercise-induced arterial hypoxaemia in healthy human subjects at sea level." *J Physiol* 355:161-75.
- Doherty, M., P. M. Smith, and K. Schroder. 2000. "Reproducibility of the maximum accumulated oxygen deficit and run time to exhaustion during short-distance running." *J Sports Sci* 18 (5):331-8. doi: 10.1080/026404100402395.
- Du Bois, D., and E. F. Du Bois. 1989. "A formula to estimate the approximate surface area if height and weight be known. ." *Nutrition* 5 (5):303-11; discussion 312-3.
- Duffield, R., B. Dawson, and C. Goodman. 2005. "Energy system contribution to 1500- and 3000-metre track running." *J Sports Sci* 23 (10):993-1002. doi: 10.1080/02640410400021963.
- Ekblom, B., P. O. Astrand, B. Saltin, J. Stenberg, and B. Wallström. 1968. "Effect of training on circulatory response to exercise." *J Appl Physiol* 24 (4):518-28.
- Epstein, Y., Y. Shapiro, and S. Brill. 1983. "Role of surface area-to-mass ratio and work efficiency in heat intolerance." *J Appl Physiol Respir Environ Exerc Physiol* 54 (3):831-6.
- Fairchild, T. J., S. Fletcher, P. Steele, C. Goodman, B. Dawson, and P. A. Fournier. 2002. "Rapid carbohydrate loading after a short bout of near maximal-intensity exercise." *Med Sci Sports Exerc* 34 (6):980-6.
- Fay, L., B. R. Londeree, T. P. LaFontaine, and M. R. Volek. 1989. "Physiological parameters related to distance running performance in female athletes." *Med Sci Sports Exerc* 21 (3):319-24.
- Fernández-Elías, V. E., N. Hamouti, J. F. Ortega, and R. Mora-Rodríguez. 2015. "Hyperthermia, but not muscle water deficit, increases glycogen use during intense exercise." *Scand J Med Sci Sports* 25 Suppl 1:126-34. doi: 10.1111/sms.12368.
- Fink, W. J., D. L. Costill, and P. J. Van Handel. 1975. "Leg muscle metabolism during exercise in the heat and cold." *Eur J Appl Physiol Occup Physiol* 34 (3):183-90.

- Flack, Virginia, and Potter Chang. 1987. "Frequency of Selecting Noise Variables in Subset Regression Analysis: A Simulation Study." *The American Statistician* 41 (1):3.
- Florence, S., and J. P. Weir. 1997. "Relationship of critical velocity to marathon running performance." *Eur J Appl Physiol Occup Physiol* 75 (3):274-8.
- Fukuba, Y., A. Miura, M. Endo, A. Kan, K. Yanagawa, and B. J. Whipp. 2003. "The curvature constant parameter of the power-duration curve for varied-power exercise." *Med Sci Sports Exerc* 35 (8):1413-8. doi: 10.1249/01.MSS.0000079047.84364.70.
- Galbraith, A, JG Hopker, SA Jobson, and L Passfield. 2011. "A novel field test to determine A novel field test to determine critical speed." *J Sports Med Doping* 01 (01):1-4.
- Galbraith, A., J. Hopker, S. Lelliott, L. Diddams, and L. Passfield. 2014. "A single-visit field test of critical speed." *Int J Sports Physiol Perform* 9 (6):931-5. doi: 10.1123/ijsp.2013-0507.
- Galloway, S. D., and R. J. Maughan. 1997. "Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man." *Med Sci Sports Exerc* 29 (9):1240-9.
- Gastin, P. B. 2001. "Energy system interaction and relative contribution during maximal exercise." *Sports Med* 31 (10):725-41.
- Gastin, P. B., and D. L. Lawson. 1994. "Influence of training status on maximal accumulated oxygen deficit during all-out cycle exercise." *Eur J Appl Physiol Occup Physiol* 69 (4):321-30.
- Gatterer, H., K. Schenk, M. Wille, C. Raschner, M. Faulhaber, M. Ferrari, and M. Burtcher. 2013. "Race performance and exercise intensity of male amateur mountain runners during a multistage mountain marathon competition are not dependent on muscle strength loss or cardiorespiratory fitness." *J Strength Cond Res* 27 (8):2149-56. doi: 10.1519/JSC.0b013e318279f817.
- Ghasemi, A., and S. Zahediasl. 2012. "Normality tests for statistical analysis: a guide for non-statisticians." *Int J Endocrinol Metab* 10 (2):486-9. doi: 10.5812/ijem.3505.
- Glass, C., R. G. Knowlton, P. B. Sanjabi, and J. J. Sullivan. 1997. "The effect of exercise induced glycogen depletion on the lactate, ventilatory and electromyographic thresholds." *J Sports Med Phys Fitness* 37 (1):32-40.
- Glass, Stephen., and Gregory Byron. Dwyer. 2007. *ACSM'S metabolic calculations handbook*. Philadelphia, Indianapolis: Lippincott Williams & Wilkins; American College of Sports Medicine.

- González-Alonso, J., C. Teller, S. L. Andersen, F. B. Jensen, T. Hyldig, and B. Nielsen. 1999. "Influence of body temperature on the development of fatigue during prolonged exercise in the heat." *J Appl Physiol (1985)* 86 (3):1032-9.
- Haseler, L. J., C. A. Kindig, R. S. Richardson, and M. C. Hogan. 2004. "The role of oxygen in determining phosphocreatine onset kinetics in exercising humans." *J Physiol* 558 (Pt 3):985-92. doi: 10.1113/jphysiol.2004.062042.
- Havenith, G., V. G. Luttikholt, and T. G. Vrijkotte. 1995. "The relative influence of body characteristics on humid heat stress response." *Eur J Appl Physiol Occup Physiol* 70 (3):270-9.
- Hill, D. W., and C. S. Ferguson. 1999. "A physiological description of critical velocity." *Eur J Appl Physiol Occup Physiol* 79 (3):290-3. doi: 10.1007/s004210050509.
- Hill, D. W., and H. Lupton. 1923. "Muscular exercise, lactic acid, and the supply and utilization of oxygen." *Q. J. Med* 16:135-171.
- Hirvonen, J., S. Rehunen, H. Rusko, and M. Härkönen. 1987. "Breakdown of high-energy phosphate compounds and lactate accumulation during short supramaximal exercise." *Eur J Appl Physiol Occup Physiol* 56 (3):253-9.
- Hoffman, M. D. 2008. "Anthropometric characteristics of ultramarathoners." *Int J Sports Med* 29 (10):808-11. doi: 10.1055/s-2008-1038434.
- Holloszy, J. O., and E. F. Coyle. 1984. "Adaptations of skeletal muscle to endurance exercise and their metabolic consequences." *J Appl Physiol Respir Environ Exerc Physiol* 56 (4):831-8.
- Ingham, S. A., G. P. Whyte, K. Jones, and A. M. Nevill. 2002. "Determinants of 2,000 m rowing ergometer performance in elite rowers." *Eur J Appl Physiol* 88 (3):243-6. doi: 10.1007/s00421-002-0699-9.
- Inoue, A., A. S. Sá Filho, F. C. Mello, and T. M. Santos. 2012. "Relationship between anaerobic cycling tests and mountain bike cross-country performance." *J Strength Cond Res* 26 (6):1589-93. doi: 10.1519/JSC.0b013e318234eb89.
- Jaafar, H., M. Rouis, L. Coudrat, E. Attiogbé, H. Vandewalle, and T. Driss. 2014. "Effects of load on wingate test performances and reliability." *J Strength Cond Res* 28 (12):3462-8. doi: 10.1519/JSC.0000000000000575.
- Jones, A. M., A. Vanhatalo, M. Burnley, R. H. Morton, and D. C. Poole. 2010. "Critical power: implications for determination of  $\dot{V}O_2\text{max}$  and exercise tolerance." *Med Sci Sports Exerc* 42 (10):1876-90. doi: 10.1249/MSS.0b013e3181d9cf7f.
- Kandel, M., J. P. Baeyens, and P. Clarys. 2014. "Somatotype, training and performance in Ironman athletes." *Eur J Sport Sci* 14 (4):301-8. doi: 10.1080/17461391.2013.813971.

- Karsten, B., E. Larumbe-Zabala, G. Kandemir, T. Hazir, A. Klose, and F. Naclerio. 2016. "The Effects of a 6-Week Strength Training on Critical Velocity, Anaerobic Running Distance, 30-M Sprint and Yo-Yo Intermittent Running Test Performances in Male Soccer Players." *PLoS One* 11 (3):e0151448. doi: 10.1371/journal.pone.0151448.
- Kent, Michael. 2006. *The Oxford dictionary of sports science & medicine*. 3rd. ed. Oxford ; New York: Oxford University Press.
- Kindermann, W., G. Simon, and J. Keul. 1979. "The significance of the aerobic-anaerobic transition for the determination of work load intensities during endurance training." *Eur J Appl Physiol Occup Physiol* 42 (1):25-34.
- Knechtle, B. 2014. "Relationship of anthropometric and training characteristics with race performance in endurance and ultra-endurance athletes." *Asian J Sports Med* 5 (2):73-90.
- Knechtle, B., P. Knechtle, U. Barandun, T. Rosemann, and R. Lepers. 2011. "Predictor variables for half marathon race time in recreational female runners." *Clinics (Sao Paulo)* 66 (2):287-91.
- Knechtle, B., P. Knechtle, T. Rosemann, and R. Lepers. 2011. "Personal best marathon time and longest training run, not anthropometry, predict performance in recreational 24-hour ultrarunners." *J Strength Cond Res* 25 (8):2212-8. doi: 10.1519/JSC.0b013e3181f6b0c7.
- Knechtle, B., P. Knechtle, T. Rosemann, and O. Senn. 2011. "Personal best time, not anthropometry or training volume, is associated with total race time in a triple iron triathlon." *J Strength Cond Res* 25 (4):1142-50. doi: 10.1519/JSC.0b013e3181d09f0f.
- Knechtle, B., A. Wirth, P. Knechtle, and T. Rosemann. 2010. "Training volume and personal best time in marathon, not anthropometric parameters, are associated with performance in male 100-km ultrarunners." *J Strength Cond Res* 24 (3):604-9. doi: 10.1519/JSC.0b013e3181c7b406.
- Kohavi, Ron. 1995. "A Study of Cross-Validation and Bootstrap for Accuracy Estimation and Model Selection." International Joint Conference on Artificial Intelligence.
- Koyal, S. N., B. J. Whipp, D. Huntsman, G. A. Bray, and K. Wasserman. 1976. "Ventilatory responses to the metabolic acidosis of treadmill and cycle ergometry." *J Appl Physiol* 40 (6):864-7.
- Kranenburg, K. J., and D. J. Smith. 1996. "Comparison of critical speed determined from track running and treadmill tests in elite runners." *Med Sci Sports Exerc* 28 (5):614-8.

- Larsson, P., and K. Henriksson-Larsén. 2005. "Combined metabolic gas analyser and dGPS analysis of performance in cross-country skiing." *J Sports Sci* 23 (8):861-70. doi: 10.1080/02640410400022078.
- Lazzer, S., D. Salvadego, E. Rejc, A. Buglione, G. Antonutto, and P. E. di Prampero. 2012. "The energetics of ultra-endurance running." *Eur J Appl Physiol* 112 (5):1709-15. doi: 10.1007/s00421-011-2120-z.
- Legaz, A., and R. Eston. 2005. "Changes in performance, skinfold thicknesses, and fat patterning after three years of intense athletic conditioning in high level runners." *Br J Sports Med* 39 (11):851-6. doi: 10.1136/bjism.2005.018960.
- Maciejczyk, M., M. Wiecek, J. Szymura, Z. Szygula, and L. E. Brown. 2015. "Influence of increased body mass and body composition on cycling anaerobic power." *J Strength Cond Res* 29 (1):58-65. doi: 10.1519/JSC.0000000000000727.
- Marino, F. E., Z. Mbambo, E. Kortekaas, G. Wilson, M. I. Lambert, T. D. Noakes, and S. C. Dennis. 2000. "Advantages of smaller body mass during distance running in warm, humid environments." *Pflugers Arch* 441 (2-3):359-67.
- McCormick, A., C. Meijen, and S. Marcora. 2015. "Psychological Determinants of Whole-Body Endurance Performance." *Sports Med* 45 (7):997-1015. doi: 10.1007/s40279-015-0319-6.
- Medbø, J. I., A. C. Mohn, I. Tabata, R. Bahr, O. Vaage, and O. M. Sejersted. 1988. "Anaerobic capacity determined by maximal accumulated O<sub>2</sub> deficit." *J Appl Physiol* (1985) 64 (1):50-60.
- Millar, N. C., and E. Homsher. 1990. "The effect of phosphate and calcium on force generation in glycerinated rabbit skeletal muscle fibers. A steady-state and transient kinetic study." *J Biol Chem* 265 (33):20234-40.
- Mimura, K., T. Nishimura, K. Yagita, K. Tanaka, and K. Maeda. 1988. "Acute effects of marathon running on postmarathon maximal oxygen uptake." *Ann Physiol Anthropol* 7 (4):231-4.
- Minetti, A. E., C. Moia, G. S. Roi, D. Susta, and G. Ferretti. 2002. "Energy cost of walking and running at extreme uphill and downhill slopes." *J Appl Physiol* (1985) 93 (3):1039-46. doi: 10.1152/jappphysiol.01177.2001.
- Miura, A., M. Endo, H. Sato, T. J. Barstow, and Y. Fukuba. 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):238-44. doi: 10.1007/s00421-002-0623-3.
- Miura, A., H. Sato, B. J. Whipp, and Y. Fukuba. 2000. "The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle ergometry." *Ergonomics* 43 (1):133-41. doi: 10.1080/001401300184693.

- Myers, J., R. Arena, B. Franklin, I. Pina, W. E. Kraus, K. McInnis, G. J. Balady, and Cardiac Rehabilitation American Heart Association Committee on Exercise, and Prevention of the Council on Clinical Cardiology, the Council on Nutrition, Physical Activity, and Metabolism, and the Council on Cardiovascular Nursing. 2009. "Recommendations for clinical exercise laboratories: a scientific statement from the american heart association." *Circulation* 119 (24):3144-61. doi: 10.1161/CIRCULATIONAHA.109.192520.
- Nimmerichter, A., N. Novak, C. Triska, B. Prinz, and B. C. Breese. 2017. "Validity of Treadmill-Derived Critical Speed on Predicting 5000-Meter Track-Running Performance." *J Strength Cond Res* 31 (3):706-714. doi: 10.1519/JSC.0000000000001529.
- Noakes, T. D. 2007. "The central governor model of exercise regulation applied to the marathon." *Sports Med* 37 (4-5):374-7.
- Noordhof, D. A., J. J. de Koning, and C. Foster. 2010. "The maximal accumulated oxygen deficit method: a valid and reliable measure of anaerobic capacity?" *Sports Med* 40 (4):285-302. doi: 10.2165/11530390-000000000-00000.
- Noordhof, D. A., P. F. Skiba, and J. J. de Koning. 2013. "Determining anaerobic capacity in sporting activities." *Int J Sports Physiol Perform* 8 (5):475-82.
- Noordhof, D. A., A. M. Vink, J. J. de Koning, and C. Foster. 2011. "Anaerobic capacity: effect of computational method." *Int J Sports Med* 32 (6):422-8. doi: 10.1055/s-0031-1271676.
- Nybo, L. 2008. "Hyperthermia and fatigue." *J Appl Physiol (1985)* 104 (3):871-8. doi: 10.1152/japplphysiol.00910.2007.
- Nybo, L., T. Jensen, B. Nielsen, and J. González-Alonso. 2001. "Effects of marked hyperthermia with and without dehydration on VO<sub>2</sub> kinetics during intense exercise." *J Appl Physiol (1985)* 90 (3):1057-64.
- Nybo, L., and B. Nielsen. 2001. "Hyperthermia and central fatigue during prolonged exercise in humans." *J Appl Physiol (1985)* 91 (3):1055-60.
- Packard, G. C., G. F. Birchard, and T. J. Boardman. 2011. "Fitting statistical models in bivariate allometry." *Biol Rev Camb Philos Soc* 86 (3):549-63. doi: 10.1111/j.1469-185X.2010.00160.x.
- Peng, Xianli, Feng Ding, Wenfeng Wu, and Xin Zhang. 2014. "Remote sensing monitoring of wind-preventing and sand-fixing effects of coastal protection forests." *Earth Observation and Remote Sensing Applications (EORSA), 2014 3rd International Workshop on*:57-61.
- Perez-Gomez, J., G. V. Rodriguez, I. Ara, H. Olmedillas, J. Chavarren, J. J. González-Henriquez, C. Dorado, and J. A. Calbet. 2008. "Role of muscle mass on sprint

- performance: gender differences?" *Eur J Appl Physiol* 102 (6):685-94. doi: 10.1007/s00421-007-0648-8.
- Peterson, M. J., S. A. Czerwinski, and R. M. Siervogel. 2003. "Development and validation of skinfold-thickness prediction equations with a 4-compartment model." *Am J Clin Nutr* 77 (5):1186-91.
- Poole, D. C., M. Burnley, A. Vanhatalo, H. B. Rossiter, and A. M. Jones. 2016. "Critical Power: an important fatigue threshold in exercise physiology." *Med Sci Sports Exerc* 48 (11):2320-2334. doi: 10.1249/MSS.0000000000000939.
- Poole, D. C., S. A. Ward, G. W. Gardner, and B. J. Whipp. 1988. "Metabolic and respiratory profile of the upper limit for prolonged exercise in man." *Ergonomics* 31 (9):1265-79. doi: 10.1080/00140138808966766.
- Rapoport, B. I. 2010. "Metabolic factors limiting performance in marathon runners." *PLoS Comput Biol* 6 (10):e1000960. doi: 10.1371/journal.pcbi.1000960.
- Robergs, R. A., F. Ghiasvand, and D. Parker. 2004. "Biochemistry of exercise-induced metabolic acidosis." *Am J Physiol Regul Integr Comp Physiol* 287 (3):R502-16. doi: 10.1152/ajpregu.00114.2004.
- Ross, E. Z., N. Middleton, R. Shave, K. George, and A. Nowicky. 2007. "Corticomotor excitability contributes to neuromuscular fatigue following marathon running in man." *Exp Physiol* 92 (2):417-26. doi: 10.1113/expphysiol.2006.035972.
- Ross, W. D., S. M. Crawford, D. A. Kerr, R. Ward, D. A. Bailey, and R. M. Mirwald. 1988. "Relationship of the body mass index with skinfolds, girths, and bone breadths in Canadian men and women aged 20-70 years." *Am J Phys Anthropol* 77 (2):169-73. doi: 10.1002/ajpa.1330770204.
- Roston, W. L., B. J. Whipp, J. A. Davis, D. A. Cunningham, R. M. Effros, and K. Wasserman. 1987. "Oxygen uptake kinetics and lactate concentration during exercise in humans." *Am Rev Respir Dis* 135 (5):1080-4. doi: 10.1164/arrd.1987.135.5.1080.
- Sahlin, K., and J. M. Ren. 1989. "Relationship of contraction capacity to metabolic changes during recovery from a fatiguing contraction." *J Appl Physiol (1985)* 67 (2):648-54.
- Sahlin, K., M. Tonkonogi, and K. Söderlund. 1998. "Energy supply and muscle fatigue in humans." *Acta Physiol Scand* 162 (3):261-6. doi: 10.1046/j.1365-201X.1998.0298f.x.
- Salah, M. A., V. S. Verla, and C. Tonga. 2012. "Anthropometric and hemodynamic profiles of athletes and their relevance to performance in the mount cameroon race of hope." *Asian J Sports Med* 3 (2):99-104.

- Saltin, B., J. Henriksson, E. Nygaard, P. Andersen, and E. Jansson. 1977. "Fiber types and metabolic potentials of skeletal muscles in sedentary man and endurance runners." *Ann N Y Acad Sci* 301:3-29.
- Sargeant, A. J. 1987. "Effect of muscle temperature on leg extension force and short-term power output in humans." *Eur J Appl Physiol Occup Physiol* 56 (6):693-8.
- Saunders, P. U., D. B. Pyne, R. D. Telford, and J. A. Hawley. 2004. "Factors affecting running economy in trained distance runners." *Sports Med* 34 (7):465-85.
- Schmid, W., B. Knechtle, P. Knechtle, U. Barandun, C. A. Rüst, T. Rosemann, and R. Lepers. 2012. "Predictor variables for marathon race time in recreational female runners." *Asian J Sports Med* 3 (2):90-8.
- Sherman, W. M., D. L. Costill, W. J. Fink, F. C. Hagerman, L. E. Armstrong, and T. F. Murray. 1983. "Effect of a 42.2-km footrace and subsequent rest or exercise on muscle glycogen and enzymes." *J Appl Physiol Respir Environ Exerc Physiol* 55 (4):1219-24.
- Sloniger, M. A., K. J. Cureton, B. M. Prior, and E. M. Evans. 1997a. "Anaerobic capacity and muscle activation during horizontal and uphill running." *J Appl Physiol* (1985) 83 (1):262-9.
- Sloniger, M. A., K. J. Cureton, B. M. Prior, and E. M. Evans. 1997b. "Lower extremity muscle activation during horizontal and uphill running." *J Appl Physiol* (1985) 83 (6):2073-9.
- Spriet, L. L. 1991. "Phosphofructokinase activity and acidosis during short-term tetanic contractions." *Can J Physiol Pharmacol* 69 (2):298-304.
- Staab, J. S., J. W. Agnew, and S. F. Siconolfi. 1992. "Metabolic and performance responses to uphill and downhill running in distance runners." *Med Sci Sports Exerc* 24 (1):124-7.
- Steininger, K., and R. E. Wodick. 1987. "Sports-specific fitness testing in squash." *Br J Sports Med* 21 (2):23-6.
- Stoutjesdijk, Philippus, and Jan Johannes Barkman. 2014. "Microclimate, vegetation and fauna." 237.
- Tanaka, K., and Y. Matsuura. 1984. "Marathon performance, anaerobic threshold, and onset of blood lactate accumulation." *J Appl Physiol Respir Environ Exerc Physiol* 57 (3):640-3.
- Tanda, G., and B. Knechtle. 2013. "Marathon performance in relation to body fat percentage and training indices in recreational male runners." *Open Access J Sports Med* 4:141-9. doi: 10.2147/OAJSM.S44945.

- Tanda, G., and B. Knechtle. 2015. "Effects of training and anthropometric factors on marathon and 100 km ultramarathon race performance." *Open Access J Sports Med* 6:129-36. doi: 10.2147/OAJSM.S80637.
- Tanner, J. M. 1949. "Fallacy of per-weight and per-surface area standards, and their relation to spurious correlation." *J Appl Physiol* 2 (1):1-15.
- Thompson, Bruce. 1995. "Stepwise Regression and Stepwise Discriminant Analysis Need Not Apply Here: A Guidelines Editorial." *Educational and Psychological Measurement* 55 (4).
- Vernillo, G., F. Schena, C. Berardelli, G. Rosa, C. Galvani, M. Maggioni, L. Agnello, and A. La Torre. 2013. "Anthropometric characteristics of top-class Kenyan marathon runners." *J Sports Med Phys Fitness* 53 (4):403-8.
- Wagner, P. D. 2000. "New ideas on limitations to VO<sub>2</sub>max." *Exerc Sport Sci Rev* 28 (1):10-4.
- Wallace, P. J., B. J. McKinlay, N. A. Coletta, J. I. Vlaar, M. J. Taber, P. M. Wilson, and S. S. Cheung. 2017. "Effects of Motivational Self-Talk on Endurance and Cognitive Performance in the Heat." *Med Sci Sports Exerc* 49 (1):191-199. doi: 10.1249/MSS.0000000000001087.
- Wegelin, J. A., and M. D. Hoffman. 2011. "Variables associated with odds of finishing and finish time in a 161-km ultramarathon." *Eur J Appl Physiol* 111 (1):145-53. doi: 10.1007/s00421-010-1633-1.
- White, M. D. 2006. "Components and mechanisms of thermal hyperpnea." *J Appl Physiol* (1985) 101 (2):655-63. doi: 10.1152/japplphysiol.00210.2006.
- White, M. D., and M. Cabanac. 1995. "Core temperature thresholds for ventilation during exercise. Temperature and ventilation." *Adv Exp Med Biol* 393:173-7.
- White, M. D., and M. Cabanac. 1996. "Exercise hyperpnea and hyperthermia in humans." *J Appl Physiol* (1985) 81 (3):1249-54.
- Willgoose, Carl, and Millard Rogers. 1949. "Relationship of somatotype to physical fitness." *J Educ Res* 42 (9):704-712.
- Wirnitzer, K. C., and E. Kornexl. 2008. "Exercise intensity during an 8-day mountain bike marathon race." *Eur J Appl Physiol* 104 (6):999-1005. doi: 10.1007/s00421-008-0855-y.
- Withers, R. T., W. M. Sherman, D. G. Clark, P. C. Esselbach, S. R. Nolan, M. H. Mackay, and M. Brinkman. 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):354-62.

Yoshida, T., M. Udo, K. Iwai, M. Chida, M. Ichioka, F. Nakadomo, and T. Yamaguchi.  
1990. "Significance of the contribution of aerobic and anaerobic components to  
several distance running performances in female athletes." *Eur J Appl Physiol  
Occup Physiol* 60 (4):249-53.

## Appendix.

### Statistical Analysis and Figures

For all statistical analysis IBM SPSS Statistics, Version 25 was used. Correlational analysis was performed using the “Bivariate Correlations” test in SPSS, with the selection of “Pearson” correlation coefficient, two-tailed tests of significance, and with significant correlation flagged by the program. Two-tailed significance was also used for the partial regressions completed in chapter 2 and 3.

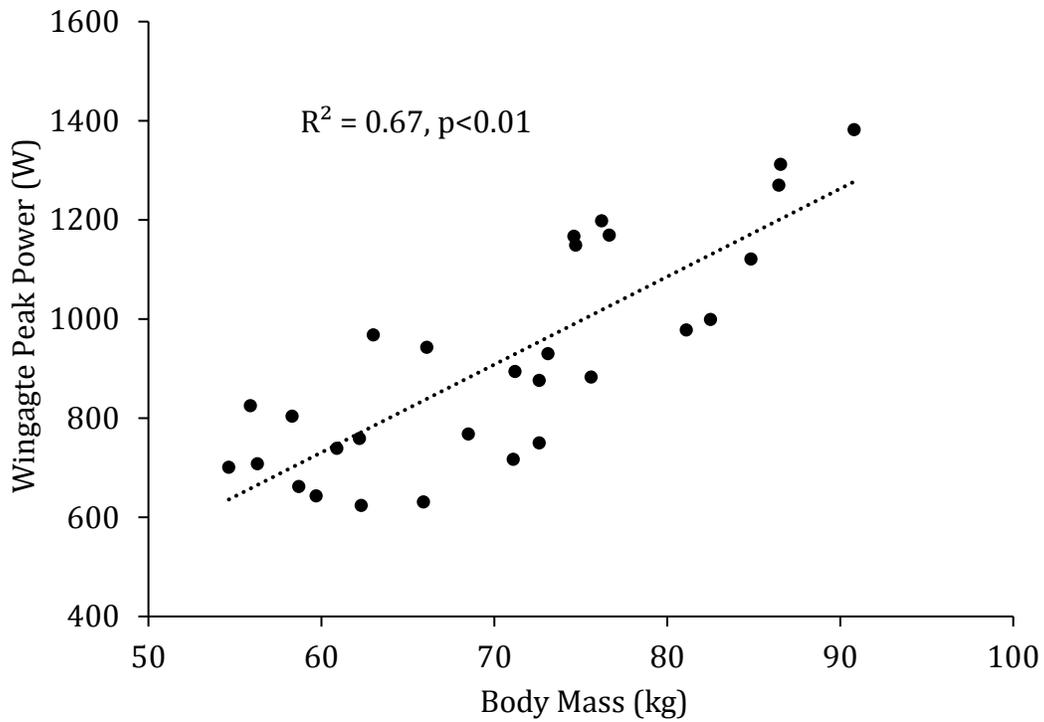
For the multiple regression analysis, several different procedures were used in SPSS. For all multiple regressions “Linear Regression” was selected with a single dependent variable of choice (i.e. finishing or hill climb times) and numerous independent variables chosen as listed in chapters 2-4. The method of selection of variables was “Stepwise” for the overall prediction of finishing or hill climb times. For specific investigations of selected variables prediction of performance, the “Enter” method was chosen to force all selected variables into the equation. This was used, for example, when investigating the combination of critical velocity and D’ for the prediction of finishing time. For the output data resulting from several key values should be observed and recorded. This includes the overall significance (p-value) of the model in the “ANOVA” output table, as well as both the Beta coefficients and p-value listed for any entered variables in the “Coefficients” output table.

All figures present in chapters 2-4 were constructed in Microsoft Excel for Mac, Version 15.38. The majority of these graphs are two variables “scatter” charts with a regression line drawn by excel. The exception is Figure 2.6, which was drawn as a “bubble” chart with the dependent variable on the y-axis, the main independent variable (critical velocity) on the x-axis and a second independent variable (D’) selected to represent the width of the bubbles.

As described in the Chapter 2 introduction there is value in including mass-controlled variables (Tanner 1949, Packard, Birchard, and Boardman 2011). Mass-adjusted variables were calculated by regressing the variable to be mass adjusted on the y-axis and body mass on the x-axis. For example, to determine mass-adjusted Wingate Peak Power a regression line was calculated to determine the equation of the

relationship between Wingate Peak Power and body mass (Fig A.1). After this was determined the residuals between the predicted Wingate Peak Power for a participant based on their mass, and their actual Wingate Peak Power was calculated. This residual value was used to represent their mass-adjusted Wingate Peak Power for prediction of finishing or hill climb times.

## Appendix Data



**Figure A.1** Example of mass-adjusted variables. Wingate Peak Power plotted as a function of body mass;  $n = 29$ . Regression line equation: Wingate Peak Power (W) =  $17.7 \cdot \text{Body Mass (kg)} - 333.46$ ,  $p < 0.01$ .