Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.
Adaptation to exercise for maximal aerobic capacity, submaximal aerobic efficiency, and cardiovascular adjustments: does the addition of heat stress induce greater improvements than exercise alone?

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Science

in

Exercise and Sport Science

Massey University, Palmerston North, New Zealand

Melissa Black

2015
Abstract

**Background:** Exercising in a hot environment often feels harder, and puts a greater amount of strain on the body than exercise in cooler temperatures. The extra strain caused by the heat has been utilised and explained extensively in the previous literature, by which training in the heat, and the concurrent physiological adaptations that arise (heat acclimation), has been shown to improve exercise performance in hot environments. It appears that the effect that heat acclimation can have on exercise performance in temperate environments, as opposed to hot, has been relatively overlooked in the literature. The physiological adaptations associated with the extra strain whilst exercising in the heat may not only induce performance benefits in temperate environments, but may also lead to positive resting cardiovascular adjustments.

**Aim:** The aim of this study was to determine what effect exercising with additional heat stress (35°C) has on maximal and submaximal aerobic capacity/performance in a moderate environment (18°C). The physiological adaptations obtained with exercise and additional heat stress was investigated, along with the impact they have on resting cardiovascular measures.

**Methodology:** In a randomised, matched control group study, eighteen moderately active males participated in a maximal and submaximal aerobic test, followed by an 11-day training protocol (five consecutive days, one day rest, six consecutive days) consisting of 60 minutes of incline walking each day on a treadmill at 50% of their VO2max in either a hot (35°C, 45% RH) or moderate (18°C, 53% RH) environment. Within four ± one day of completing the training protocol, the maximal and submaximal aerobic tests were repeated. Maximal aerobic capacity was measured in the maximal test; with submaximal VO2, heart rate and lactate measured to indicate changes during exercise. Core temperature, heart rate, plasma volume, forearm blood flow, whole body sweat rate, local sweat rate, and perceptual measures were taken throughout the 60 minutes of walking over the 11-day training period, in combination with resting heart rate and blood pressure measures to determine cardiovascular adjustments.

**Results:** Exercise, with or without heat stress improved maximal aerobic capacity by 7.0 ± 0.9 mL·kg⁻¹·min⁻¹ (p < 0.001), although, additional heat stress did not improve maximal aerobic capacity above exercise alone. The exercise protocol, irrespective of whether in a hot or moderate environment, lowered submaximal heart rate (p = 0.008) and relative VO2 (p < 0.001), but had no effect on submaximal blood lactate. The 11-day training protocol lowered resting heart rate (p < 0.001), reduced core temperature (p = 0.039), increased forearm blood flow (p = 0.046), and lowered perceived exertion (p < 0.001) for both groups. Additionally, the heat group had increased whole
body sweat rate ($p = 0.01$), and improved thermal comfort ($p = 0.024$). The exercise, regardless of environment, appeared to induce resting cardiovascular adjustments, although statistical significance was not reached.

**Conclusions:** Eleven days of exercise at 50% of VO$_2$max, regardless of environment, can improve maximal and submaximal performance in a moderate environment and induce positive cardiovascular adjustments. Eleven days of exercise in 35°C can induce heat acclimation, illustrated through an increase in whole body sweat rate, and a reduction in exercising heart rate, core temperature and perceived exertion.
Acknowledgements

Firstly, I would like to thank my supervisors; Dr Toby Mündel, and Dr Darryl Cochrane. Darryl, your support through not only this thesis, but through my two years as a post-graduate student has been outstanding and I could not have asked for more, thank you. Toby, where do I even start! The amount of support, knowledge, and enthusiasm you have offered from under-graduate through to post-graduate study has been second to none, and undoubtedly the reason I have progressed this far and developed a passion for research, I cannot thank you enough.

To Karl and Blake, thank you for all your support and assistance from pilot work and data collection, all the way to the completion of this thesis. Your help and knowledge in the lab was irreplaceable, and a special thank you must go to you both for constantly having to move “that bloody treadmill” for me.

To my participants, a massive thank you is in order for the time and effort you put into completing my study; I could not have done it without each one of you.

Finally, to my family; your support and interest in not only this thesis, but also everything else that I choose to take part in has been especially important to me. I would not be where I am today without the love and support you provide, and for that I thank you so very much.
# Table of Contents

Abstract .................................................................................................................................................................................... II
Acknowledgements ................................................................................................................................................................................ IV
Table of Contents ............................................................................................................................................................................... V
List of Abbreviations ........................................................................................................................................................................ VIII
List of Tables ......................................................................................................................................................................................... XII
List of Figures .................................................................................................................................................................................... XIII

Chapter One: Introduction .................................................................................................................................................................. 1

Chapter Two: Literature Review ...................................................................................................................................................... 3

2.1 Human Thermoregulation ................................................................................................................................................... 3
  2.1.1 Heat Exchange Modalities .................................................................................................................................................. 4
    2.1.1.1 Heat Balance ............................................................................................................................................................. 6
    2.1.1.2 Heat Exchange Parameters .......................................................................................................................................... 7
    2.1.1.3 Section Summary .......................................................................................................................................................... 9

2.2 Temperature Regulation at Rest .............................................................................................................................................. 10
  2.2.1 Autonomic Regulation ........................................................................................................................................................ 10
    2.2.1.1 Skin Blood Flow .......................................................................................................................................................... 11
    2.2.1.2 Eccrine Sweating ....................................................................................................................................................... 13
    2.2.1.3 Shivering ................................................................................................................................................................. 15
    2.2.1.4 Section Summary ..................................................................................................................................................... 17

2.3 Temperature Regulation during Exercise .......................................................................................................................... 18
  2.3.1 Physiological Responses .................................................................................................................................................. 18

2.3.2 Exogenous Heat Stress ...................................................................................................................................................... 21
  2.3.2.1 Physiological Responses ................................................................................................................................................ 22
  2.3.2.2 Effect on Performance ................................................................................................................................................... 27
    2.3.2.2.1 Fixed-Intensity Exercise ........................................................................................................................................... 29
    2.3.2.2.2 Self-Paced Exercise ............................................................................................................................................... 30
    2.3.2.2.3 VO₂max Performance .............................................................................................................................................. 31
  2.3.2.3 Strategies to Minimise Performance Decrements ........................................................................................................... 32
    2.3.2.3.1 Cooling and Pre-Cooling ....................................................................................................................................... 32
    2.3.2.3.2 Hydration ............................................................................................................................................................... 33
    2.3.2.3.3 Heat Acclimation .................................................................................................................................................... 33
  2.3.2.4 Section Summary ........................................................................................................................................................ 34

2.4 Heat Acclimation ........................................................................................................................................................................ 35
  2.4.1 Experimental Protocols ..................................................................................................................................................... 35
    2.4.1.1 Environmental Conditions ........................................................................................................................................ 36
    2.4.1.2 Exercise Protocol Duration, Intensity and Modality ................................................................................................. 37
    2.4.1.3 Methods of Acclimation ............................................................................................................................................. 38
  2.4.2 Physiological Adaptations to Heat Acclimation .................................................................................................................. 41
Chapter Five: Results

5.1 Maximal Aerobic Capacity Test ................................................................. 66
5.2 Submaximal Aerobic Test ........................................................................ 67
5.3 Training Results ........................................................................................ 68

5.3.1 Resting and Cardiovascular Measures .................................................. 68
5.3.2 Heart Rate ............................................................................................... 69
5.3.3 Core Temperature .................................................................................. 70
5.3.4 Whole-body Sweat Rate ................................................................. 71
5.3.5 Plasma Volume Change .................................................................... 72
5.3.6 Forearm Blood Flow ........................................................................... 73
5.3.7 Mean Skin Temperature .................................................................... 74
5.3.8 Blood Pressure .................................................................................... 74
5.3.9 Haemoglobin and Haematocrit ......................................................... 74
5.3.10 Local Sweat Rate ............................................................................... 74
5.3.11 Rating of Perceived Exertion ............................................................... 74
5.3.12 Thermal Comfort .............................................................................. 76
5.3.13 Thermal Sensation ............................................................................ 76

Chapter Four: Methodology ........................................................................ 58

4.1 Experimental Overview ........................................................................... 58
4.1.1 Participants .......................................................................................... 58
4.1.2 Pre- and Post-Training Sessions .......................................................... 59
4.1.3 Training Protocol ................................................................................. 61
4.1.4 Justification of Methodology ............................................................... 62
4.2 Experimental Procedures ........................................................................ 63
4.2.1 Measurements .................................................................................... 63
4.3 Statistical Analysis .................................................................................. 65

Chapter Three: Research Aim and Hypotheses ........................................ 57
5.3.14 $V\text{O}_2$ .................................................................................................................................................... 76
5.3.15 Respiratory Exchange Ratio ............................................................................................................... 77
5.3.16 Metabolic Rate .................................................................................................................................. 77
5.3.17 Correlations ....................................................................................................................................... 77

Chapter Six: Discussion .................................................................................................................................. 78

6.1 The impact of training and heat stress on maximal and sub-maximal aerobic performance .......... 78
6.2 Physiological responses during the 11-day training protocol .............................................................. 81
6.3 The impact of exercise and additional heat stress on resting cardiovascular adjustments ............ 84
6.4 Considerations/Limitations .................................................................................................................. 84
6.5 Future research ................................................................................................................................... 86

Chapter Seven: Conclusions .......................................................................................................................... 87

References ............................................................................................................................................................. 88

Appendices ............................................................................................................................................................ 105

  Participant Information Sheet ..................................................................................................................... 105
  Health Screening Questionnaire .................................................................................................................. 110
  Pre-Exercise Health Screening Questionnaire .......................................................................................... 110
  Consent Form ............................................................................................................................................. 114
  Ethical Letter of Approval .......................................................................................................................... 115
  Cultural Consideration for Ethical Approval ............................................................................................. 116
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
<tr>
<td>BLa</td>
<td>Blood lactate</td>
</tr>
<tr>
<td>BMI</td>
<td>Body mass index</td>
</tr>
<tr>
<td>BSA</td>
<td>Body surface area</td>
</tr>
<tr>
<td>b·min⁻¹</td>
<td>Beats per minute</td>
</tr>
<tr>
<td>CBF</td>
<td>Cerebral blood flow</td>
</tr>
<tr>
<td>cm</td>
<td>Centimetres</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>ECF</td>
<td>Extracellular fluid</td>
</tr>
<tr>
<td>EHS</td>
<td>Exertional heat stroke</td>
</tr>
<tr>
<td>FI</td>
<td>Fixed-intensity</td>
</tr>
<tr>
<td>Hb</td>
<td>Haemoglobin</td>
</tr>
<tr>
<td>Hct</td>
<td>Haematocrit</td>
</tr>
<tr>
<td>HPL</td>
<td>Human Performance Laboratory</td>
</tr>
<tr>
<td>HSP</td>
<td>Heat shock protein</td>
</tr>
<tr>
<td>ISF</td>
<td>Interstitial fluid</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit Description</td>
</tr>
<tr>
<td>--------</td>
<td>------------------</td>
</tr>
<tr>
<td>K</td>
<td>Kilograms</td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>kg·m$^{-2}$</td>
<td>Kilogram per square metre</td>
</tr>
<tr>
<td>km</td>
<td>Kilometres</td>
</tr>
<tr>
<td>km·h$^{-1}$</td>
<td>Kilometres per hour</td>
</tr>
<tr>
<td>L</td>
<td>Litres</td>
</tr>
<tr>
<td>L</td>
<td>Litre</td>
</tr>
<tr>
<td>L·min$^{-1}$</td>
<td>Litres per minute</td>
</tr>
<tr>
<td>L·h$^{-1}$</td>
<td>Litres per hour</td>
</tr>
<tr>
<td>LSR</td>
<td>Local sweat rate</td>
</tr>
<tr>
<td>M</td>
<td>Metres</td>
</tr>
<tr>
<td>m</td>
<td>Metre</td>
</tr>
<tr>
<td>m·s$^{-1}$</td>
<td>Metres per second</td>
</tr>
<tr>
<td>MCAv$_{mean}$</td>
<td>Middle cerebral artery mean blood velocity</td>
</tr>
<tr>
<td>mL</td>
<td>Millilitres</td>
</tr>
<tr>
<td>mL·kg$^{-1}$·min$^{-1}$</td>
<td>Millilitres per kilogram per minute</td>
</tr>
<tr>
<td>min</td>
<td>Minute</td>
</tr>
<tr>
<td>mm</td>
<td>Millimetre</td>
</tr>
<tr>
<td>mm Hg</td>
<td>Millimetres of mercury</td>
</tr>
<tr>
<td>mmol·L$^{-1}$</td>
<td>Millimoles per litre</td>
</tr>
<tr>
<td>μL</td>
<td>Microlitre</td>
</tr>
<tr>
<td>Na$^+$/K$^+$ ATPase</td>
<td>Sodium-potassium adenosine triphosphatase</td>
</tr>
<tr>
<td>NE</td>
<td>Norepinephrine</td>
</tr>
<tr>
<td>NO</td>
<td>Nitric oxide</td>
</tr>
<tr>
<td>O</td>
<td>Oxygen</td>
</tr>
<tr>
<td>O$_2$</td>
<td>Oxygen</td>
</tr>
</tbody>
</table>
PV  Plasma volume

RER  Respiratory exchange ratio
RH  Relative humidity
RPE  Rating of perceived exertion

SD  Standard deviation
SE  Standard error
SkBF  Skin blood flow
SP  Self-paced
STPD  Standard temperature and pressure, dry
SWR  Whole body sweat rate

Tc  Core temperature
ThC  Thermal comfort
ThS  Thermal sensation
Tsk  Skin temperature
Tsk  Mean skin temperature

USG  Urine specific gravity

Ve  Minute ventilation
\( \dot{V}O_2 \)  Oxygen consumption
\( \dot{V}O_2\text{max} \)  Maximal oxygen uptake
VOP  Venous occlusion plethysmography
WBGT  Wet-bulb globe temperature
List of Tables

Table 2.1. The physiological adaptations obtained during passive heating, exercise in a hot environment, and exercise in a cool environment (Armstrong & Maresh, 1991). ................................................................................................................................. 42

Table 2.2. Time-course for the decay of heat acclimation from three different studies (Armstrong & Maresh, 1991). ........................................................................................................................................................................... 49

Table 2.3. Previous studies investigating the effect of short- to long-term heat acclimation protocols on performance in a hot environment (30-50°C). ..................................................................................................................... 52

Table 2.4. Previous studies investigating the effect of heat acclimation protocols on performance in a cool/moderate environment (10-25°C). ............................................................................................................................. 55

Table 4.1. Physical characteristics and initial aerobic performance of the control and heat groups .......... 59

Table 5.1. Percent VO₂max at the four submaximal stages during the pre- and post-training submaximal test for the heat and control groups. ................................................................................................................................. 67

Table 5.2. Mean responses during the submaximal protocol pre- and post-training in the heat and control groups........................................................................................................................................................................... 67

Table 5.3. Mean differences between pre- and post-training for the heat and control groups. ..................... 68

Table 5.4. Mean responses on day 1, 5, and 11 of the 11-day training protocol for measures taken at 0 min and 30 min in the heat and control groups. ........................................................................................................................................................................ 75

Table 5.5. Mean responses on day 1, 5, and 11 of the 11-day training protocol for measures taken at 30 min and 60 min in the heat and control groups. ........................................................................................................................................................................ 75

Table 5.6 Correlations between % change in VO₂max from pre- to post-training and alterations in heart rate, rectal temperature, plasma volume and forearm blood flow as a result of the 11-day training protocol .......... 77
List of Figures

**Figure 2.1.** Thermoregulation within the body and the mechanisms for control (Campbell, 2008) ......................... 4

**Figure 2.2.** Efferent neuronal pathways for control of skin vasomotor tone, nonshivering thermogenesis, and shivering in the rat (Campbell, 2008). .............................................................................................................................................. 10

**Figure 2.3.** The typical bi-phasic cutaneous vasodilation during 30 minutes of local warming at 42°C (Charkoudian, 2003). ............................................................................................................................................ 13

**Figure 2.4.** The interactions and contributions of core temperature and skin temperature to sweat rate (Shibasaki et al., 2006). ........................................................................................................................................... 15

**Figure 2.5.** Heat exchange at rest and during cycling exercise at increasing rates of work (Powers & Howley, 2009). .................................................................................................................................................................... 19

**Figure 2.6.** Alterations to metabolic heat production and evaporative, convective, and radiative heat loss over the course of a 25 minute submaximal exercise bout in a cool environment (Powers & Howley, 2009) .......... 20

**Figure 2.7.** Skin blood flow at rest and during dynamic exercise (Powers & Howley, 2009). ...................................................... 20

**Figure 2.8.** Heat production and contributions of evaporation, convection, and radiation to heat loss during exercise at a range of environmental temperatures (Powers & Howley, 2009). .......................................................................................... 22

**Figure 2.9.** Core temperature over a range of differing air temperatures at three different exercise intensities (Armstrong, 2000). ........................................................................................................................................... 23

**Figure 2.10.** Physiological changes during exercise in the heat (Casa, 1999) ................................................................. 24

**Figure 2.11.** Core temperature responses during fixed-intensity exercise (A), and self-paced exercise (B) in a hot environment (Schlader et al., 2010). ........................................................................................................................................... 28

**Figure 2.12.** Estimated percentage decrement in marathon finishing time with increasing Wet-Bulb Globe Temperature (WBGT) (Ely et al., 2007). ........................................................................................................................................... 31

**Figure 2.13.** Core temperature responses on days 1, 4, 8, and 12 of a 12-day constant work-rate heat acclimation regime (A); or a controlled-hyperthermia heat acclimation regime (B) (Taylor & Cotter, 2006) ..... 40

**Figure 2.14.** Amount of time to develop the physiological adaptations associated with the development of heat acclimation (Armstrong & Maresh, 1991). ........................................................................................................................................... 41

**Figure 2.15.** Changes to sweat rate as a result of physical activity and heat acclimation (Nadel et al., 1974). ... 45

**Figure 4.1.** General overview of the testing procedure completed over a four week period for the control group (n=9) and the heat group (n=9). A = Pre- and post-training maximal aerobic capacity tests; B = Pre- and post-training submaximal aerobic tests; C = 11-day training protocol. ........................................................................................................................................... 58

**Figure 4.2.** Overview of the maximal-test visit to the HPL in the week before and after training for the control group (n=9) and the heat group (n=9). ........................................................................................................................................... 60

**Figure 4.3.** Overview of the submaximal test and familiarisation visits to the HPL in the week before and after training, for the control group (n=9) and the heat group (n=9). ........................................................................................................................................... 60

**Figure 4.4.** Overview of each of the training days in the 11-day training protocol for the control group (n=9) and the heat group (n=9). ........................................................................................................................................... 61

**Figure 5.1.** Effect of an 11-day training protocol on ............................................................................................................. 66

**Figure 5.2.** Heart rate (mean ± SE) at 0 min and 60 min of the 60 min exercise bouts on day 1, 5 and 11 of the 11-day training protocol for the heat group (n=9) and the control group (n=9). ........................................................................................................................................... 69
Figure 5.3. Core temperature (mean ± SE) at 0 min and 60 min of the 60 min exercise bouts on day 1, 5 and 11 of the 11-day training protocol for the heat group (n=9) and the control group (n=9). .............................................. 70

Figure 5.4. Whole body sweat rate (mean ± SE) on day 1, 5 and 11 of the 11-day training protocol for the heat group (n=9) and the control group (n=9)........................................................................................ ...................... 71

Figure 5.5. Plasma volume change (mean ± SE) at rest (0 min) between days 1 and 5, and days 1 and 11 of the training protocol for the heat group (n=9) and the control group (n=9).............................................................. 72

Figure 5.6. Forearm blood flow (mean ± SE) at 0 min and 30 min of the 60 minute exercise bouts on day 1, 5 and 11 of the 11-day training protocol for the heat group (n=9) and the control group (n=9). ......................... 73