# HUMAN BEHAVIORAL TEMPERATURE REGULATION: AN EXERCISE APPROACH

Zachary J. Schlader BSc., MSc.

A thesis submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

School of Sport and Exercise
Massey University
Palmerston North
New Zealand

September 2011

## ABSTRACT

Behavior represents our most preferred and effective modality by which body temperature is regulated. However, knowledge concerning the control of this behavior in humans is relatively limited. Therefore, the overall purpose of this thesis was to further our understanding of the control of human thermoregulatory behavior. This was accomplished by firstly establishing self-paced exercise and heat stress as a thermal behavioral model, while secondly the control of this behavior was investigated. In the first part of this thesis, voluntary reductions in exercise intensity have been found to be associated with thermal discomfort and reductions in heat production, which presumably improved heat exchange between the body and the environment over time, and ultimately aided body temperature regulation. Thus, these experimental data associatively indicate that reductions in exercise intensity in the heat are thermoregulatory behaviors, suggesting that self-paced exercise in the heat is a valid model by which to evaluate human thermal behavior. The studies presented in the second part of this thesis systematically evaluated the control of this behavior. It was subsequently demonstrated that skin temperature and the accompanying alterations in thermal perception and the percentage of peak oxygen uptake elicited by a given exercise intensity are all modulators of exercise intensity, and thus thermal behavior, in the heat. Notably, reductions in peak oxygen uptake appear to play a minimal role. Importantly, these studies strengthened the associations observed in the first part of this thesis by specifically establishing a causative relationship between exercise intensity and temperature regulation. Furthermore, the experimental observations also indicated that thermal behavior during self-paced exercise is ultimately initiated by the perception of effort response. In conclusion, the findings presented in this thesis suggest that a voluntary reduction in exercise intensity occurring in the heat is a thermoregulatory behavior, and that this behavior can be directly elicited by changes associated with elevations in skin temperature. During such instances, thermal perception and the percentage of peak oxygen uptake elicited by a given exercise intensity have been uniquely identified as contributors to this behavior. The findings of this thesis improve our understanding of the control of human thermoregulatory behavior.

# ACKNOWLEDGEMENTS

I would firstly like to thank my supervisors Drs. Toby Mündel and Stephen Stannard. I am forever indebted to the time, guidance, support, criticism, and advice you have given me. Specifically, Toby, I am eternally grateful for your endorsement of a random American student's scholarship application to study in New Zealand, without this support none of this would have been possible. A special thank you also goes out to the Human Performance Laboratory manager Matt Barnes, your technical support and advice were essential to this thesis. Likewise, I want to thank all of the people who participated in the studies comprising this thesis. Without your time and dedication, this thesis would truly have been impossible. Furthermore, I would to thank Education New Zealand, for without their support through the International Doctoral Research Scholarship I would not have had the tremendous opportunity to come to Massey University. Finally, but most importantly, I would like to thank my beautiful wife, Cassie, for being awesome and for your unwavering love and support throughout my, seemingly never ending, life as a student. None of this would have been possible without your encouragement and unquestioned willingness to move to the other side of the world!

# TABLE OF CONTENTS

# LIST OF ABBREVIATIONS

**A**

| | |
|---|---|
| ANOVA | Analysis of variance |
| A-V $O_2$ | Arteriovenous oxygen content difference |
| A-V $CO_2$ | Arteriovenous carbon dioxide content difference |

**B**

| | |
|---|---|
| bpm | Beats per minute |
| BSA | Body surface area |

**C**

| | |
|---|---|
| $\dot{C}$ | Rate of heat exchange via convection |
| °C | Degrees centigrade |
| $CO_2$ | Carbon dioxide |
| CNS | Central nervous system |
| $\dot{C}_{res}$ | Rate of heat exchange from respiratory conduction |

**D**

| | |
|---|---|
| DBP | Diastolic blood pressure |

**E**

| | |
|---|---|
| $\dot{E}$ | Rate of heat loss via evaporation |
| EEG | Electroencephalogram |
| $\dot{E}_{max}$ | Maximal rate of evaporative cooling for heat balance |
| EMG | Electromyogram |
| $\dot{E}_{req}$ | Required rate of evaporative cooling for heat balance |
| $\dot{E}_{res}$ | Rate of heat exchange from respiratory evaporation |

**G**

| | |
|---|---|
| g | Gram |

**H**

| | |
|---|---|
| h | Hour |
| $h_c$ | Convective heat transfer coefficient |
| HR | Heart rate |
| HRpeak | Peak heart rate |
| %HRpeak | Percentage of peak heart rate |
| HSI | Heat strain index |
| $H_2O$ | Water |

**J**

| | |
|---|---|
| J | Joule |

**K**

| | |
|---|---|
| $\dot{K}$ | Rate of heat exchange via conduction |
| $K^+$ | Potassium |
| Kg | Kilogram |
| kJ | Kilojoule |
| kPa | Kilopascal |

**L**

| | |
|---|---|
| L | Liter |
| LCG | Liquid conditioning garment |
| LF | Linear factor |
| LR | Lewis relation |

**M**

| | |
|---|---|
| m | Meter |
| $\dot{M}$ | Metabolic rate |
| MAP | Mean arterial pressure |
| $m_b$ | Body mass |
| min | Minute |
| mmHg | Millimeters of mercury |
| mmol | Millimole |
| mOsm | Milliosmole |

**N**

| | |
|---|---|
| $Na^+$ | Sodium |

**O**

| | |
|---|---|
| $O_2$ | Oxygen |

**P**

| | |
|---|---|
| $P_A$ | Ambient water vapor pressure |
| $PO_{RPE\ 16}$ | Power output at a rating of perceived exertion of 16 |
| $PO_{70\%}$ | Power output at 70% of maximal rate of oxygen uptake |
| PSI | Physiological strain index |
| $P_{Sk}$ | Saturated water vapor pressure at the skin |

**Q**

| | |
|---|---|
| $\dot{Q}$ | Cardiac output |
| $\dot{Q}peak$ | Peak cardiac output |
| $\%\dot{Q}peak$ | Percentage of peak cardiac output |

**R**

| | |
|---|---|
| r | Correlation coefficient |
| $\dot{R}$ | Rate of heat exchange via radiation |
| RER | Respiratory exchange ratio |
| RPE | Rating of perceived exertion |
| rpm | Revolutions per minute |

**S**

| | |
|---|---|
| s | Second |
| $\dot{S}$ | Rate of heat storage/loss |
| SD | Standard deviation |
| SBP | Systolic blood pressure |
| SEM | Standard error of the mean |

**T**

| | |
|---|---|
| $T_A$ | Ambient temperature |
| $T_{aHYP}$ | Anterior hypothalamic temperature |
| $\bar{T}_b$ | Mean body temperature |
| $T_C$ | Core body temperature |
| thermoTRP | Temperature sensitive transient receptor potential ion channel |
| TPR | Total peripheral resistance |
| $\bar{T}_{Sk}$ | Mean skin temperature |
| TRPM8 | Transient receptor potential ion channel Melastatin 8 |
| TRPV1 | Transient receptor potential ion channel Vanilloid 1 |
| TRPV3 | Transient receptor potential ion channel Vanilloid 3 |

**V**

| | |
|---|---|
| *v* | Air velocity |
| $\dot{V}CO_2$ | Rate of carbon dioxide elimination |
| $\dot{V}O_2$ | Rate of oxygen uptake |
| $\dot{V}O_2max$ | Maximal rate of oxygen uptake |
| $\dot{V}O_2peak$ | Peak rate of oxygen uptake |
| $\%\dot{V}O_2peak$ | Percentage of the peak rate of oxygen uptake |

**W**

| | |
|---|---|
| W | Watt |
| $\dot{W}$ | Rate of heat exchange from the generation of external work |

**Y**

| | |
|---|---|
| y | Year |

# LIST OF FIGURES

# LIST OF TABLES