Thermal perception and physiological responses in males and females during mild cold exposures in different clothing ensembles

by

Jingkai Pang

B.Sc., 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

© Jingkai Pang 2016

SIMON FRASER UNIVERSITY

Summer 2016

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:	**Jingkai Pang**
Degree:	**Master of Science**
Title:	***Thermal perception and physiological responses in males and females during mild cold exposures in different clothing ensembles***
Examining Committee:	**Chair: William Cupples** Professor

Matthew D. White, Ph.D
Senior Supervisor
Associate Professor

François Haman, Ph.D
Co-Supervisor/Supervisor
Associate Professor

Christopher T. Minson
External Examiner
Professor
Department of Human Physiology
University of Oregon

Date Defended/Approved: June 13, 2016

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

In the first study of this thesis 10 males and 10 females walked on a treadmill with a ~10 km/h wind and an ambient temperature of -8°C. The hypotheses tested included: 1) females will have lower skin temperature and surface heat flux while all other physiological responses are similar when compared to male, 2) within each sex, an elasticized (E) coat versus a non-elasticized (NE) coat would give a diminished physiological strain and 3) that within each sex, the E coat versus the NE coat would give a better thermal comfort. Results in this first study showed some differences in physiological responses between the sexes, that males had higher thermal comfort ratings in an E versus a NE coat during exercise ($p<0.05$). In the second study, it was hypothesized that females would have greater sensitivity to skin temperature changes than males on the hand, back and chest. The results showed females versus males were less sensitive to temperature changes only on the chest ($p <0.05$). In conclusion, in the first study some physiological responses differed between the sexes, the E compared to the NE coat provided no beneficial physiological responses within each sex and finally the E versus the NE coat provided greater thermal comfort in males. In the second study females were less sensitive to cold stimuli on the chest compared to males.

Keywords: Cold Stress; Clothing Physiology; Cutaneous Temperature Sensitivity; Exercise; Sex; Thermal Comfort

Dedication

I would like to dedicate this thesis to my friends and family. To all my friends and family thank you for always being there and supporting my endeavours. Your support, motivation and inspiration were a blessing throughout my education.

Acknowledgements

I would like to thank all those who have helped me throughout my graduate studies. First of all I would like to thank my supervisor, Dr. Matthew White, as well as Dr. François Haman for their wisdom, knowledge and expertise. I would also like to thank all my lab mates for all their support: Sukhi Sahota, Lauren Penko, Matthew Dorton, Mike Rogers and Corrine Malcolm. Thank you to members of Mountain Equipment Co-op including Sara Lanyon, Spring Harrison, Greg Scott and Joël Mertens. This thesis would also not be possible without the help of members of the department: King Chao, Joe Wang and Joel Blok. I would also like to thank everyone who helped with data collection and various task around the lab: Jaiden Choi, Emily Lefler, Sadia Nyab and Sebastian Weber. Finally, thank you to all the volunteers who took the time out of their busy schedules to participate in this study.

Table of Contents

List of Tables

List of Figures

List of Acronyms

ANOVA	Analysis of Variance
BAT	Brown Adipose Tissue
BMI	Body Mass Index
CEW	Cold Exercise Walking
CEWA	Cold Exercise Walking with Arms
CRS	Cold Rest Sitting
CST	Cutaneous Temperature Sensitivity Testing
E	Elasticized
EMG	Electromyography
HF	Heat Flux
HR	Heart Rate
LH	Luteinizing Hormone
NE	Non-Elasticized
NPY	Neuropeptide Y
NST	Non-Shivering Thermogenesis
mHF	Mean Surface Heat Flux
mT_{SK}	Mean Skin Temperature
ST	Shivering Thermogenesis
TC	Thermal Comfort
T_{RE}	Rectal Temperature
TRP	Transient Receptor Potential
T_{SK}	Skin Temperature
VO_2	Rate of Oxygen Consumption
WRS	Warm Rest Sitting

Glossary

Air Permeability	Rate of air flow passing through the surface of the fabrics (32)
Brown Adipose Tissue	Adipose tissue found in the body with a capability to release heat, especially during non-shivering thermogenesis (83)
Clothing Ventilation	Is a method to measure movement of air or other ventilating gas in the clothing's microenvironment (32)
Conduction	Heat exchange through collisions between molecules in contact (55)
Convection	Heat transfer by mass motion through a fluid (55)
Neuropeptide Y	Neurotransmitter of the autonomic system that initiates vasoconstriction (49)
Neuropeptide Y Receptor	A G-protein coupled receptor that is activated by Neuropeptide Y and peptide YY that is involved in vasoconstriction (49)
Non-Shivering Thermogenesis	Heat exchange when exposed to cold that is associated with non-shivering mechanism such as brown adipose tissue (83)
Periphery	Outer region of the body
Temperature sensitive neurons	Sensory neurons that respond to changes in their temperature (71)
Thermal discrimination	The ability to detect small changes in temperature (30)
Transient Receptor Potential	Ion channels that mediate pain, temperature, pressure and vision (71)

Executive Summary

This thesis investigates the effect of mild cold exposure on physiological and cognitive responses of males and females while wearing different clothing ensembles during light exercise. The first chapter of this thesis gives a literature review on physiological responses in cold environments, heat exchange principles, differences in these cold physiological responses between the sexes, cutaneous temperature sensitivity, the effect of menstrual cycle on female body temperature, clothing physiology plus physiological and cognitive responses to the cold. The chapter is completed with a rationale for the studies in the thesis as well as the hypotheses that are addressed in the two studies given in the thesis. The second chapter presents a study on the effect of different clothing ensembles on cold on physiological and thermal comfort responses between sexes during light exercise. It was hypothesized for the same cold conditions and same light intensity exercise that males and females in each coat type would have similar core temperatures, oxygen consumption rate, and heart rate but females would have lower skin temperature and surface heat flux. Our results did not have the hypothesized outcomes, absolute oxygen consumption rate was greater in males compared to females and heart rate were significantly greater in females compared to males due to their greater apparent relative work rate. Skin temperatures and heat flux were not different between sexes. It was also hypothesized that within each sex, an E coat would give a diminished physiological response to the cold compared to a NE coat for core temperature, oxygen consumption rate, heart rate, skin temperature and surface heat flux. Our results were not in agreement with this hypothesis, as females had a significantly lower skin temperature when wearing an E coat compared to a NE coat. Finally it was hypothesized that an E coat would give a better regional and overall thermal comfort relative to that of a NE coat. For males, our results were in agreement with our hypothesis as males reported significantly greater thermal comfort at multiple sites and overall during cold exercise wearing an E version coat compared to a NE coat during exercise with arm movement whereas females had no differences in thermal comfort between the two coat types. The third chapter presents a study on sex differences of cutaneous temperature sensitivity responses to surface cold in males and females and how cutaneous thermosensitivity participates in the overall thermoregulatory response to cold. It was hypothesized that females would be more sensitive to cutaneous temperature changes compared to males. Our results did not support our hypothesis that females would be more sensitive to cutaneous temperature changes compared to males. On the dorsum of the hand and upper back males and females had the same cutaneous temperature sensitivity and contrary to the hypothesis, females were less sensitive on the chest compared to males.

Chapter 1.

Introduction

Exposure to the cold induces heat loss and disrupts thermal balance which leads to responses by the body's thermoregulatory system so as to regulate core temperature (3). These responses include vasoconstriction in the periphery, shivering thermogenesis (ST) from skeletal muscle contractions, and non-shivering thermogenesis (NST) from brown adipose tissue and/or skeletal muscles, which results in the release of heat from macronutrients and aids in the maintenance of thermal balance (7, 69, 78). Initial effects of the cold on the human body leads to a decrease in peripheral skin temperature due to vasoconstriction and reductions in skin temperature alone can induce an increase in both ST and NST (3, 84). With an acute exposure long enough to induce a decrease in core temperature this also contributes to the induction of these cold defense responses (78). Cognitively, in these cold conditions there is a decrease in thermal comfort which is influenced by factors including sex (5) core temperature and skin temperature (72). There is also supporting evidence that suggests the role of cutaneous temperature sensitive neurons that express transient receptor potential (TRP) membrane channels are important for detecting cold and enabling an appropriate cold response (71). TRPA1 channels are activated by noxious cold when dry bulb temperature is less than 17˚C while TRPM8 operates between 25 to 28˚C. These receptors are located on the free endings of the A δ and C fibers and may be critical for linking cognitive responses and physiological responses to cold exposure (47, 71).

An essential aid to help sustain thermal balance in humans is the use of clothing or technical apparel. In a cold environment, clothing help in slowing the rate of heat loss due to convection and conduction from the body surface to the ambient environment by providing a microenvironment between the skin and clothing (32). Autonomic thermoregulatory and behavioral responses, the latter including choice of protective clothing, allows exposure to environments with mild to extreme cold with the maintenance of thermal comfort.

1.1. Literature Review

1.1.1. Physiological Response to Cold Stress

Heat Exchange

Clothing and other behavioural thermoregulation strategies are effective at aiding humans to maintain thermal balance in cold environments. When cold stress overcomes the effectiveness of behavioural thermoregulation, there is a whole body physiological response to the cold that will assist with maintaining thermal balance and contribute to the regulation of core temperature. The net rate of heat storage (S) to and from the human body is determined by the sum of the Metabolic ($+H_M$), conductive ($\pm H_{CD}$), convective ($\pm H_{CV}$), radiative ($\pm H_R$) and evaporative ($\pm H_{EV}$) rates of heat exchange and rate external work (W) (Equation 1) (2, 55).

$$S = H_M \pm W \pm H_{CD} \pm H_{CV} \pm H_R \pm H_{EV} \text{..........(Equation 1)}$$

Heat transferred from metabolic activity is dissipated to the blood vessels which results in convective heat exchange to the tissues which transfers heat by conduction and convection to the surface of the skin (9). Once heat has been transported to the surface of the skin, it can be dissipated to the environment. Heat exchange also occurs between the human body and the environment through conduction, convection, radiation and evaporation. If the net balance or heat storage is positive then there is an overall heat gain by the body, and if it heat storage is negative then there is an overall heat loss by the body.

The human body will utilize conduction and convective heat exchange to transfer heat to the environment during cold stress (2, 81). Conduction rates vary depending on how much surface area is in direct contact with the ground or other objects. At rest standing upright only about 3% of total body surface area is in contact with the ground, and while lying supine there can be an increase of about 8-12% of total body surface area (2).

Convection, heat dissipation to and from the body surface to the surrounding gas or liquid, is influenced by the convective heat transfer coefficient which takes into account the diffusion of gas or liquid and bulk convective movement of heat and the ambient temperature and skin temperature (2). As the heat transfer coefficient is a property of the liquid or gas responsible for convection there is a difference in heat exchange due to cold air versus cold water immersion. It is suggested that the convective heat exchange from cold water compared to cool air is up to 70 times larger for identical temperature conditions (55, 91). It is also important to realize that there is a gradient of heated air surrounding the body with air in a cool environment becoming progressively cooler a greater distances from the skin surface. Moving air disrupts this gradient and instead cool air is often in contact with the skin surface. With disruption of this gradient, wind increases convective heat exchange at the body surface (55, 65). This is especially important in clothing physiology. In a moving individual the core is relatively stable in movement compared to the extremities. The swinging motion of the extremities during movement, cause a greater heat dissipation as air is being disrupted faster (63). This contributes to a greater heat loss due to convection on the extremities compared to the core body (63).

Vasomotor Cold Response and Convective Heat Exchange: Skin Temperature

During cold exposure, the body attempts to regulate core temperature with a peripheral cutaneous vasoconstriction that is critical for maintaining thermal balance (55). As core temperature decreases, there is an increase of peripheral vasoconstriction. Lopez et al. (54) have shown that onset of vasoconstriction occurs when esophageal temperature was decreased to 36.7^0C in males and to 37.1^0C in females when skin temperature were held at 36.6^0C. The underlying mechanism for vasoconstriction is controlled by sympathetic nervous system (9, 49, 78). The decrease in skin and core temperature results in a release of norepinephrine by sympathetic fibers. Norepinephrine then acts on α_1 and α_2 receptors of the vascular smooth muscle of the cutaneous arterioles which promotes vasoconstriction (49). Plasma norepinephrine levels monitored during cold immersion study and were found to increase along with metabolic rate during the immersion period (46). Frank et al. (24) used cold saline-infusion to highlight the role of norepinephrine's immediate role in the cold response and showed a decrease in skin and core temperature due to increase norepinephrine concentration in the blood. As well, there is evidence that supports neuropeptide Y acting as a co-transmitter in promoting vasoconstriction (49). Neuropeptide Y is released by sympathetic fibers and acts on NPY Y1 receptors to promote vasoconstriction of the smooth muscle of the cutaneous arterioles (49).

With peripheral vasoconstriction, there is a decrease in blood flow to the extremities or the periphery (8, 70). This has the thermoregulatory advantage of decreasing the convective heat exchange capabilities of the body with the ambient environment as less heat is being transported to the surface of the skin (2). As well, due to a reduction in the core compartment size, which includes the region of the deep organs, from vasoconstriction, there is an increase in thermal insulation (8, 12). Overall thermal insulation of the core increases as skin temperature decreases (8, 80). While vasoconstriction may aid in defending core temperature, due to decrease in blood flow to the periphery, this gives an increased susceptibility to cold injury as temperatures and perfusion can drop severely depending on the length and magnitude of cold exposure.

Due to differences in subcutaneous tissue distribution in the arms and the legs, there is an increase in blood flow to the arms compared to the legs due to less subcutaneous tissue (59). As McArdle et al. demonstrates this results in a greater convective heat exchange at the upper body compared to the lower body for the same metabolic rate (58, 59). McArdle et al. show that there is a greater core temperature decrease in an arm exercise protocol compared to a leg exercise protocol for the same metabolic rate due to greater convective heat exchange when using the upper body compared to the lower body (58). This emphasizes the importance of analyzing whole body exercise protocols when performing light exercise in the cold instead of focusing on just the lower limbs or the upper limbs.

Metabolic Heat Transfer, Oxygen Consumption and Heart Rate in Cold Environments

Cold-induced increases of heat release from skeletal muscle make an important contribution to regulation of aiding core temperature. The body relies on shivering of skeletal muscle for core temperature regulation, shivering is involuntary muscle contractions that contribute to maintaining thermal balance in the cold. Shivering can increase metabolic rate by two to five times compared to resting metabolic rate (19, 59, 90). TRP channels TRPA1 and TRPM8 in cutaneous cold sensitive neurons detect a decrease in skin temperature, as well as afferent A fibers, group II delta & group IV dorsal root fibers which integrate at the dorsomedial hypothalamus (16). The shivering signal is sent down the spinal cord via the lateral column utilizing alpha and gamma motor neurons to activate skeletal muscle contractions and this gives a release of metabolic heat. These asynchronous muscle fiber contractions also gives energy released from the hydrolysis of high energy phosphate bonds in ATP (69). ST and NST can be quantified and measured using electromyography (EMG), indirect calorimetry and direct calorimetry.

Metabolic heat from skeletal muscle through either voluntary skeletal muscle contraction or shivering can be quantified using indirect calorimetry to give whole-body oxygen consumption (VO_2). During an increase in metabolic heat transfer from skeletal muscle there is an increase in VO_2. For ST, it was originally believed that longer exposure to cold will result in a decrease in glycogen use (56). Studies investigating passive rewarming refute this belief as individuals who rewarm from a hypothermic state by ST showed no difference in rewarming response if they had low or normal in glycogen stores, as monitored by muscle biopsy (62). As more muscles begin to shiver this will lead to an increase in VO_2 (19). This has allowed the development of predictive formulas for determining the metabolic response due to shivering or light exercise (19). An increase in VO_2 from skeletal muscle metabolic activity will result in an increase demand for oxygen by the body (19). The net result is an increase in cardiac output (55) comprised of increases in both heart rate and stroke volume.

The rate at which metabolic heat exchange is occurring due to voluntary physical activity is highly dependent on intensity, environmental conditions, and type of exercise (58). At low intensity physical activity in a cold environment, VO_2 is seen to either be higher or the same compared to warm temperature condition (58, 92). If metabolic activity from exercise is insufficient in maintaining both core and skin temperature, ST will aid in maintaining thermal balance by increasing metabolic activity. In low intensity physical activity, heart rate has been reported to be lower in cold conditions than compared to warm conditions while there is an increase in stroke volume to increase cardiac output compared to warm conditions (92). It is believed the increase in cardiac output is due to an increase in cardiac preload from an increase in central blood volume from vasoconstriction due to cold stress (55, 92). Consequently, in the cold one should expect lower heart rates than what might be expected for the same intensity exercise in warm conditions. It is important to note, that when utilizing clothing in the cold, the ‘hobbling effect’. The hobbling effect is the binding of clothing to the body, can increase the workload and therefore heart rate for the participant (64). It is also important to note that thermal insulation from muscle and fat changes when resting and performing exercise. Park et al. (67) have shown that during exercise body insulation decreases by ~75% from that at rest.

Differences in Physiological Cold Defense Response between the Sexes

A cold response is seen in both males and females after there are decreases of either core body temperature or skin temperatures. Cold exposure leads to vasoconstriction, ST and NST to regulate core temperature (3, 49, 83). Evidence suggests, however, that due to the physiological and anatomical differences in males and females, there is a difference in the cold response between sexes (85). Wagner & Horvath measured and monitored physiological responses of men and women between the ages of 20 and 30 during cold air exposure at 10^0C who wore minimal clothing and found that women have more stable core temperatures compared to men, more rapid metabolic responses compared to men and a lower skin temperature compared to men when exposed to the cold (85). Wagner & Horvath attribute the physiological sex difference due to body composition and the role of body adiposity in assisting with thermal insulation (85). Body size, body shape, body composition and hormonal effects of the menstrual cycle may all be responsible for differences in physiological responses to the cold between sexes (8, 55). With respect to body composition, women on average have larger amount of subcutaneous adipose tissue compared to men. Females aged 20 to 29 were reported to have an average body fat percentage of 10-54% while males aged 20 to 29 had a body percentage ranging from 5-38%(18). Thicker amounts of subcutaneous tissue will result in greater thermal insulation and would theoretically minimize heat dissipation from the body to the environment (55, 67, 92). While core temperature is effectively maintained due to thermal insulation and a more pronounced vasoconstriction, the extremities are more susceptible to cold injury. This highlights the importance of proper clothing selection in cold environments (8). Males and females will display similar core temperature decreases at ambient temperatures as low as 5^0C but there is a difference of 1-2^0C lower skin temperature in women compared to males (33). This has been attributed to a more pronounced vasoconstriction seen in women which results in a decrease in arterial blood flow to the extremities such as the hand and feet. (8). Due to a more pronounced vasoconstriction which results in a lower skin temperature at the hands and feet in females compared to males, females are more susceptible to cold injury and thus there is an emphasis on providing proper insulation through clothing design to protect females from cold stress and minimizing the risk of cold injury (8, 55).

When comparing identical thermal insulation between women and men, women have greater surface area to volume ratio and smaller body mass (59). This results in a larger surface area for convective heat exchange to occur thus leading to greater heat dissipation. When similar body fat percentage women and males were immersed in 20^0C cold-water, women rectal temperature dropped by 1.6^0C, while men rectal temperature dropped by only 1.1^0C (59). When body fat percentage is controlled, there is a sex difference in core temperature regulation possibly due to difference in surface area and body mass between sexes.

With respect to metabolic activity differences between sexes, the literature indicates that cold air exposure will result in a net increase in overall metabolic heat transfer but women and men show similar increases in its magnitude (8, 91). When the type of thermogenesis is partitioned into ST and NST it is shown that young women show a 15% greater NST compared to males due to a delay in the shivering response in females (86). The onset of shivering was shown to be delayed in women, occurring 0.3 to 1.2^{0}C later for the same ambient temperatures compared to males (86).

Tikuisis et al.'s result reinforce that sex differences in thermoregulation are due to body composition as they found no differences in rectal temperature cooling and metabolic rates between sexes when exposed to cold water at 18^{0}C after correcting for body fatness and body surface area (82).

Transient receptor potential (TRP) channels participate in temperature sensation and are another factor that could play a role in cold response. The TRP channels are found in temperature sensitive neurons (71) and temperature detection is determined by these TRP channels. There are various classes of TRP channels that operate on a wide range of temperatures. TRP channels that are relevant to the cold response are the TRPM8 and TRPA1. TRPM8 operates between 25 to 28˚C and can also be activated by menthol and isiothiocyanates (47, 71, 74). TRPA1 is more actively seen in extreme cold environments as it is activated when temperatures decrease below 17˚C (47). Agonists for the TRPA1 include menthol, clove oil and ginger (47, 71). These channels transmit their temperature detection to Aδ and C fibers which travel through the dorsal horn of the spinal cord and integrate at the dorsal medial hypothalamus (47, 71). These TRP channels are the putative link between cold sensitive neurons and both thermal perception as well as physiological responses to the cold. Cutaneous temperature sensitivity testing is a means of assessment of temperature sensitivity in humans. , this method it is reasoned will give a better understanding of the relationship between TRP channels and the physiological cold response plus it may help identify the physiological reason as to why males and females respond to cold differently.

1.1.2. Cutaneous Temperature Sensitivity

It is argued that cutaneous temperature sensitivity, specifically peripheral thermosensitivity, may play an important role in determining temperature dependent behavioural responses (29, 30). Gerr & Letz (27) in a comprehensive study of 4,462 male Vietnam-era veterans evaluating the adverse health effects of those who served in the war, suggest that cutaneous thermal thresholds are influenced by many different factors including body mass index (BMI) (27), race (27, 76), age (4, 17, 76), and skin temperature (23, 27). In Gerr & Letz's (27) comprehensive study found that BMI, skin temperature, smoking and race have moderate positive effects on finger thermal thresholds, while smoking, race, age, height, and BMI had positive association with toe thermal thresholds. Additionally, the effects of thermode probe application have also shown to be an influential factor in thermal threshold testing (36). The biological mechanism for these variables effect on thermal thresholds, however, remains unknown.

While Gerr and Letz (27) and others (17, 27, 30, 34, 48, 52, 53) analyzed influences such as age, BMI and height involved with thermal threshold detection, no agreement has been reached on the sex specific differences in cutaneous thermal thresholds between males and females. Golja et al. have shown that females have lower thermal thresholds compared to males, specifically females have greater *thermal discrimination*. Thermal discrimination is the ability to detect small changes in surface skin temperature compared to males, however there is a lack of a clear physiological explanation for these differences (17, 30, 53). Golja et al.'s (30) study improved on previous thermal threshold studies by using non-elderly volunteers and by using an equal number of males and females. A previous study only looked at elderly population and unequal number of males and females supporting that the study's results may not be applicable to younger populations (14). Golja et al. (30) hypothesized that differences in thermosensitivity among sexes could be related to a greater temperature sensitive neuron density in women when compared to men (11). The larger quantity of cutaneous temperature sensitive neurons in females versus males they reasoned would lead to greater spatial summation of receptor signals leading to greater thermosensitivity at all ranges of temperatures (21). Alternatively, they also suggest from their research that differences in thermosensitivity between sexes may be due to greater skin thickness among men compared to women which would lead to an increase time to respond to a temperature stimulus for men, indicative of lower thermosensitivity (30). While Golja et al. looked at sex differences in thermal thresholds, their study did not control for fluctuations in core temperatures due to the menstrual cycle in women. As sex is important factor in thermal threshold detection, it is necessary to identify differences in thermal threshold among sexes to properly understand the underlying physiological mechanism involved in thermosensitivity and the cold response.

1.1.3. Menstrual Cycle & Body Temperature

When looking at differences in male and female thermal thresholds as well as differences in physiological responses and thermal comfort votes in cold environments it is important to be aware of the hormonal effects of the female menstrual cycles on core temperature, skin blood flow and skin temperature (57). Physiologically, estradiol, luteinizing hormone (LH) and progesterone have a strong influence on the vascular activity and this leads to menstrual cycle-dependent changes in core temperature (50). Estradiol and progesterone each increase in concentration during the luteal phase (50). High plasma concentrations of progesterone cause the cutaneous vasodilation threshold to shift to higher core temperatures and also affects the water-sodium balance (10). Consequently, high plasma concentrations of progesterone results in an increase in core temperature of about 0.3 to 0.6^0C following ovulation during the luteal phase compared to the follicular phase in females. Sodenberg et al. (79)

investigated the effects of thermal cold perception during late follicular, mid-luteal phase and early follicular phase and found a significantly lower thermal cold perception threshold during late follicular phase and mid-luteal phase compared to early follicular phase. Sodenberg et al. (79) believe that these differences are attributed to high estradiol concentration which they claim act on the thin myelinated fibers influencing thermal perception. So for studies of thermal thresholds the study design needed requires data on female menstrual cycle, specifically which phase the female volunteers are experiencing during testing session so that the effects of the menstrual cycle can be properly taken into account.

1.1.4. Clothing Physiology

Clothing Thermal Properties

A major component of the human physiological response to the cold is behavioural and this includes utilizing protective clothing or technical apparel. The basic thermal insulation properties of clothing help with retaining warmth and allowing for humans to survive in cold weather conditions (37-39, 43). Thus a comprehensive understanding of the clothing construction is essential for understanding the cognitive as well as physiological responses to the cold. The ideal clothing design for cold environment focuses on minimizing heat loss due to cold stress (35). Humans wearing clothing are in a dynamic environment and when they are moving or exercising this affects the ability for clothing to prevent heat loss. When designing clothing for cold environments, to account for fluctuating conditions, clothing should be able to optimally protect at a wide range of temperatures (35, 44). While there is a focus on preventing heat loss, there is also consideration for preventing heat accumulation from exercise in cold environments (39). For clothing testing 5 major components can be assessed: heat resistance, vapour resistance, water tightness, air permeability and wicking (35).

The basic thermal insulation or heat resistance is an intrinsic property of clothing independent of the environment. Thermal insulation represents the resistance to heat exchange between the skin and the clothing surface due to convective or radiative heat exchange (35). In the cold it is important for retention of heat, while in hot conditions it is important for preventing heat accumulation. The main mode of heat exchange in clothing apparel is through convection of heat to and from the air (68).

Thermal insulation is the reciprocal of clothing conductivity. Gagge et al developed the clo unit for thermal insulation that is an expression of the amount of thermal insulation expressed per unit surface area (25). One clo is defined as the thermal insulation required to keep a clothed resting individual warm and comfortable at an ambient temperature of 21°C in a room ventilation with of air at 1 m/s (13, 25). Higher clo values correspond to a specific fabric giving more insulation.

Thermal insulation values can be determined using static thermal manikins or using a hot plate apparatus that emits a temperature gradient (35). Heat loss through a fabric sample at a set temperature gradient from the static thermal manikin or hot plate is assessed at a set ambient temperature. As these types of tests are static and as such they are often poor representation of human physiology. The thermal insulation values do not provide an absolute determination of clothing thermoregulatory properties and effectiveness in active settings (43, 44). In a dynamic setting there is movement, humidity differences and changes in wind velocity. These can greatly influence the thermal effectiveness of clothing. To aim for more practical thermal insulation values, thermal insulation corrected values are required and employed to more accurately represent the thermal insulation of clothing (43, 44).

One of the design methods employed in cold weather technical apparel to retain heat is by minimizing the circulation of air due to convection in the microenvironment. The microenvironment is the space between the inner layer of clothing and the surface of the skin (32). The convection in the microenvironment is dependent on clothing ventilation which has an inverse relationship between air permeability and thermal insulation of clothing (32, 35). It is reasoned that constructions that maximize retention of still air will perform better in cold weather conditions as they resist the cooling due to convection (32). A phenomenon known as ‘clothing pumping’ occurs when there is human movement while wearing clothing. This results in circulation of trapped air with the ambient environment. With ‘clothing pumping’ there is a decrease in microenvironment temperature due to convection in the clothing-skin microenvironment (32). It is believed with proper fabric selection and garment construction, clothing ventilation can be minimized to provide an ideal microenvironment for humans in cold conditions. This suggests that an elasticized version of a winter coat with ‘box baffles’ relative to a non-elasticized winter coat will provide a greater maintenance of thermal balance as it will minimize the loss of still air due to or convection evident with ‘clothing pumping’.

Water penetration must also be taken into consideration when selecting proper fabric for clothing design in cold environments. If water is able to penetrate the clothing layer in cold environment, there will be a greater amount of heat loss due to convection to the surrounding environment (35). Proper waterproofing is necessary to ensure adequate defense against convective heat loss. When designing clothing with waterproofing in mind, it is important to note that water proofing will reduce vapour permeability (35). This could affect the ability for the clothing to perform ideally in exercise conditions, as the ability to remove excess heat accumulation by evaporation becomes more difficult. Waterproofing is also advantageous in assisting with wind proofing of clothing (35). A proper balance of waterproofing and vapour permeability is required to reach ideal maintain temperatures over a wide range in cold environments with light exercise.

Wicking has an important role in assisting with thermal comfort during cold exposure. Discomfort is often reported when liquid is present on the skin (35, 72). Proper wicking fabrics are effective at removing liquids from the skin, this aids in removing skin surface sweat which facilitates evaporation (32). With the removal of sweat from the skin, there will be removal of discomfort. While this may not be an important property in static cold exposure, proper wicking is necessary in exercise conditions and is applicable for clothing designed for workers in the cold (35). Assessment of wicking ability has been performed by hanging strips of fabric, wetting them for a fixed period of time and then quantifying their ability to wick (35). Newer objective measures of assessing wicking of fabrics have employed electrical conductivity testing which involved running a current to quantify the water absorption speed of the fabric (35).

Fabric Selection

In recent years, there is an increased focus on developing athletic apparel designed to maintain thermal balance and keep the athlete cool due to a demand for increase in performance. Specifically, in performance athletic wear such as for running, there is a need to keep athletes dry and cool during physical activity. This trend has led to increased research in fabric analysis and selection (43). In hot environments, a major component of sports apparel fabric is the ability to wick sweat away from the skin into the clothing allowing for cooling of the skin temperature (32). Similarly, ventilation must be considered as well. Air movement is important in cooling the body as flowing air will cool the body while trapped air would keep the wearer warm. Thus when assessing clothing ventilation there is an inverse relationship between air permeability and thermal insulation (32). The more permeable the clothing ensemble the less the ensemble will be able to retain heat in the microenvironment and thus will result in a cooler environment (42).

A previous study focused on the size of the fabric: small, medium and large knits – representing differences in air permeability with the large knits representing highest air permeability and the small knits representing the lowest air permeability (31). The results showed that the large knits gave a lower torso skin temperature as well as a lower perceived hotness (31).

When selecting for fabrics there are two major factors to consider: Absorption ability and moisture transport in clothing (32). Natural fibers such as cotton and wool have very effective absorption ability as they can wick moisture from the skin much better than other fabrics (15). Due to their strong absorption ability, however, natural fibers also retain the sweat in the fabric much longer compared to other fabrics (15). Furthermore, cotton and wool also have low thermal conductivities which may lead to higher core and skin temperature in exercise activities (40, 43).

Conversely, in hot environments synthetic fabrics such as polyester are not very effective at sweat absorption. However, these fabrics are very effective in transport of moisture through clothing. Heat loss due to evaporation of sweat is more accessible to the ambient environment in synthetic fabrics. Due to the strong absorption properties of cotton and wool, they retain the moisture and cannot spread the moisture to other regions of the fabric (32). From these fabric properties, there is an increase focus on creating fabric blends that can maximize both water absorption and moisture transport. Currently, a mixture of these fabrics consisting of 92% nylon and 8% spandex has been shown to be the most promising at maximizing water absorption and moisture transport compared to other fabric blends (45).

In terms of clothing fabric assessment, there is much needed focus on replicating exercise conditions (13, 42). Clothing fabric choices are most often assessed in conditions seen in general work (38, 42). Due to the rise in popularity of sport specific fabric analysis there is a need for fabric testing in exercise conditions seen in the sport of interest. For example, many fabric tests used long-sleeve shirts. For many sports short-sleeve shirts are much more commonly used and recent studies have shown differences in results between long-sleeved shirts and short-sleeved shirts in maintaining thermal balance (26).

While fabric choices have been shown to have influence on skin temperature in resting conditions, the evidence supports that there is no significant thermal balance differences between synthetic and natural fabrics during work-related condition (45, 51). There is a need for assessments in exercise conditions to establish any potential differences in thermal balance between synthetic and natural fabrics.

Thermal Manikins

Thermal manikins are an effective research instruments used in clothing physiology. During the early 1940s, the earliest research thermal manikins were developed and this consisted of a single segment copper manikin for military purposes (44). Thermal manikin have been developed and improved for over 60 years. There are hundreds of manikin iterations, each milestone bringing on significant improvements and features (Table 2).

Thermal manikins in clothing assessment is a popular resource used to study clothing heat transfer characteristics (44, 60). A wide variety of measurements can be tested when using thermal manikins and these include: thermal insulation of clothing, sweating rate and air movement around the human body (60). The thermal manikin can be used to simulate human body heat exchange with the environment as well as whole body and local heat fluxes. Thermal manikins also allow measurement of heat exchange, integration of dry heat losses, objective measurements of clothing thermal insulation and they help by providing clothing insulation and evaporative resistance values for prediction models (44). Thermal manikins also can be used in many different environmental conditions including those with high or low ambient temperatures, with humid or dry air and with or without wind (44).

Early prototypes of thermal manikins could only change temperature on a whole-body level (44). During the development process it was clear to researchers that there was a need to control multiple individual segments in thermal manikins to replicate human physiology. This has led to current thermal manikins to control at least 15 body segments or function as a single whole body (44, 60). Multiple segment control has led to thermal manikin assessment in asymmetric thermal environments (44). The ability to control these segments contributes to improved heat radiation and accuracy of measurements (60). Additionally, the development of joint-moving manikins have helped simulate human movement and exercise thus providing a more accurate representation of human physiology.

Current reliability and reproducibility of thermal manikins in research settings have been maximized to an acceptable range from previous iterations of thermal manikins (1, 44). Repeatability within labs has a variability of about 2-4% in thermal insulation measurements (44). Between labs, reproducibility has a variability of about 5-10% (44). Future developments of thermal manikins require standardization of construction and build among the industry (44). With standardization, this can lead to improving accuracy and reliability in research involving thermal manikins.

In recent years thermal manikins have been moving forward in two distinct directions. Similar to the history of thermal manikin, one path continues to develop multi-function thermal manikins in research settings. Major breakthroughs include thermal manikins that can produce sweat and mimic human walking movements. As well there has been a creation of gender specific manikins (44). The other trend in thermal manikin development is the creation of simple, reliable cost effective thermal manikins (44). This trend is popular in industry settings and most often these types of thermal manikins use whole-body control for assessing thermal insulation.

While thermal manikins are effective at assessing static thermoregulatory responses in clothing physiology, they are less effective in dynamic situations. Furthermore, with respect to human clothing testing a large component is related to thermal comfort and cognitive response. At this time, thermal manikins are unable to provide thermal comfort responses and this is a significant limitation in cold clothing physiology.

1.1.5. Thermal Perception at Rest and Light Exercise

Human Cognitive Response to the Environment

Temperature sensitive neurons in the skin are integrated into the peripheral nervous system and play a role in thermal perception (74). Through thermal perception an individual can determine if they are in a state of thermal comfort or if they can perceive an uncomfortable thermal state. Thermal comfort is defined as the satisfactory or indifferent response to the thermal environment (72). The main determinants of thermal comfort are suggested to be both core and skin temperatures (22, 73). When comparing hyperthermic and normothermic conditions, Schlader et al. determined that skin temperature was more influential on thermal comfort compared to core temperature (72, 73). Schlader et al. cooled skin temperature while increasing the core temperature through exercise and found that subjects still felt thermally comfortable (22, 72, 73). Additionally, when core temperature was maintained while skin temperature was increased there were increased reports of thermal discomforts. During cooling, once hyperthermic state was achieved core temperature showed to be the main factor determining thermal comfort (72). Consequently, Schlader et al. concluded that skin temperature was more influential on thermal comfort compared to core temperature for hyperthermic conditions (73). In exercise in the heat, recent research suggest that skin wetness due to sweating also influences thermal comfort (20). It is believed that once a certain amount of sweat is generated thermal comfort decreases due to this unwanted wet stimuli from sweat (20).

Thermal sensation also plays an important role in behavioural responses to changes in temperature. Thermal sensation is described as the ability to discriminate temperature differences in a thermal environment (73). From extensive research in thermal sensation, evidence suggest that thermal sensation is mainly influenced by skin temperature during both rest and exercise (22, 87). Gerrett et al. suggest, however, that thermal sensation may be less sensitive during exercise compared to rest as a larger change in temperature is required to be detectable (28). Thus, skin temperature is an important factor in thermal sensation, and may play an influencing role when considering cutaneous temperature sensitivity evaluations such with a cooled thermode probe.

Sex Differences in Thermal Perception

Tikuisis et al. and Wagner & Horvath suggest that thermoregulatory changes in core and skin temperature are mostly due to sex differences in body composition (82, 85). Karjalainen (2012) in a review on the topic of gender and thermal comfort, and pilot studies in our lab, show that females have similar core and skin temperature changes in response to cold relative to males. It is then expected that males and females would experience similar thermal comfort in identical climate conditions; however, this result is reported infrequently. Instead, thermal comfort results reveal that females typically report a much colder experience than males (48). It is reasoned that this difference arises from differences in cutaneous temperature sensitivity between sexes. Golja et al. show females are still more thermosensitive compared to males without control for hormonal differences in menstrual cycle (30). Consequently for studies of thermal comfort the literature supports that females will report lower thermal comfort in similar conditions compared to males. Investigating the relationship between thermal comfort and cutaneous temperature neurons may reveal the mechanism as to why these differences are commonly reported. This knowledge has important considerations on design of clothing for active females in cold environments.

1.2. Rationale

Studies have shown that the cold response between sexes is different due to both physiological and anatomical influences (8, 59, 82). As well, in identical climatic conditions, females have reported a lower thermal comfort compared to males (48). Previous literature links these differences to body composition, adiposity and thermal insulation. Park et al. (67) have shown that during exercise body insulation decreases by ~75% from that at rest, however, when females and males are compared in cold exercise conditions there is still difference in physiological responses to the cold (58). Recent research in TRP channels suggest that cold response differences between sexes is due to difference in cutaneous temperature sensitive neurons density (30). There is evidence that females are more sensitive through cutaneous temperature sensitivity testing to the cold in the periphery compared to males (30). It is reasonable to believe that temperature sensitive neurons may contribute to the underlying physiological mechanism involved in thermosensitivity and cold responses.

Cognitive responses to the cold are typically with the utilization of protective clothing. Basic thermal insulation properties of clothing aid in retaining warmth and thermal comfort in cold weather conditions through minimization of conductive heat exchange (40, 41). Through ‘clothing pumping’ from movement in cold environment, undesirable circulation of trapped air occurs and results in cooling of the skin and core temperature as well as thermal comfort (2). It follows that an elasticized version winter coat, that minimized the effects of ‘clothing pumping would be more effective in maintaining thermal balance and thermal comfort.

1.3. Hypothesis

1.3.1. Study 1: Effect of Mild Cold Exposure on Cognitive and Physiological Responses between Males and Females Wearing Different Clothing Ensembles

It was hypothesized for the same cold conditions and same light intensity exercise that males and females in each coat type would have similar core temperatures, oxygen consumption rate, and heart rate but females would have lower skin temperature and surface heat flux. It was also hypothesized that within each sex, an elasticized coat that minimizes clothing ventilation would give a diminished physiological responses to the cold compared to a non-elasticized coat for core temperature, oxygen consumption rate, heart rate, skin temperature and surface heat flux. It was hypothesized that within each sex, the elasticized coat would give a better regional and overall thermal comfort relative to that of a non-elasticized coat.

1.3.2. Study 2: Differences in Cutaneous Temperature Sensitivity between Males and Females

After controlling for confounding influences of thermode application pressure, for cutaneous temperature sensitivity testing using the method of limits and method levels, it was hypothesized that females would be more sensitive to temperature changes on the skin compared to males. It was also hypothesized that females would be more sensitive to temperature changes on the skin on the dorsum of the hand, chest, and upper back compared to males when assessed using the Method of Levels and Method of Limits.

Chapter 2.

Effect of Mild Cold Exposure on Cognitive and Physiological Responses between Males and Females Wearing Different Clothing Ensembles

2.1. Introduction

Under a cold stress, the human body responds with both a vasomotor response to give a peripheral vasoconstriction and a metabolic response comprised of Shivering Thermogenesis (ST) and Non Shivering Thermogenesis (NST) that collectively helps regulate core temperature (3, 49, 84). Due to underlying physiological and anatomical differences, males and females respond differently to cold exposure (85). Wagner & Horvath showed that during cold air exposure at 10°C, while wearing minimal clothing, women relative to men have more stable core temperatures, more rapid metabolic responses and a lower skin temperature (85). Wagner & Horvath concluded physiological sex differences are due to body composition and the role of body adiposity in assisting with thermal insulation. Tikuisis et al. also concluded that sex differences during cold exposure in thermoregulation are due to body composition as they found no differences in rectal temperature cooling and metabolic rates after correcting for body fatness and body surface area (82). Current literature supports that body adiposity is an important determinant of thermal insulation and core temperature regulation for both sexes when exposed at rest to cold environments (8, 82, 85).

The sex related differences in the physiological cold response are less clear during exercise. Park et al investigated the percent contribution of insulation from muscle and from fat to total body insulation. They found that as exercise intensity increased, there is a progressive drop in total body insulation to a value of ~ 25% of the resting value (67). Park et al’s study showed the 75% drop of total body insulation was due to the removal of skeletal muscle insulation, as it became perfused during exercise, and this supports the need for excellent thermal protection from winter garments during exercise in cold environments.

Evidence indicates that sex differences to cold are not limited to physiology. Rather, there are reports of sex differences for thermal comfort vote responses to the same cold stress (48). Previous pilot studies in our lab and as shown in the literature review by Karjalanina, support that females who experience identical cold stress as men while wearing similar clothing ensembles report a lower thermal comfort (48). It is reasoned that this difference arises from differences in cutaneous temperature sensitivity between sexes as reported on in study 2 in Chapter 3 of this thesis.

One of the first behavioural responses is using clothing to assist in maintaining core and skin temperatures. Cold weather technical apparel is designed to minimize circulation of air due to convection and to provide a warm microenvironment for the individual (2, 32, 41). Ideally, cold weather technical apparel minimizes clothing ventilation and maximizes thermal insulation to help improve thermal comfort of the user.

One technical apparel design approach to improve winter coat performance is to create ‘box baffles’ with circumferential elastic bands to minimize clothing ventilation. The success of these ‘box baffles designs’ should be reflected by a higher skin temperature and lower surface heat flux while maintaining core temperature compared to a non-elasticized coat without box baffles. Furthermore, as clothing ventilation would be minimized, the elasticized version of the coat with box baffles should give greater thermal comfort when compared to a non-elasticized version in identical cold conditions. It was hypothesized for the same cold conditions and same light intensity exercise that males and females in each coat type would have similar core temperatures, oxygen consumption rate, and heart rate but females would have lower skin temperature and surface heat flux. It was also hypothesized that within each sex, an elasticized coat would give a diminished physiological responses to the cold compared to a non-elasticized coat for core temperature, oxygen consumption rate, heart rate, skin temperature and surface heat flux. It was also hypothesized that within each sex, the elasticized coat would give a better regional and overall thermal comfort relative to that of a non-elasticized coat.

2.2. Methods

2.2.1. Ethics

Approval for this study was obtained from the Simon Fraser University Office of Research Ethics. Each participant was provided the option of removing themselves from the study at any point at ant any time, without reason.

2.2.2. Participants

The participant was given an orientation in the laboratory of the equipment involved in this study and an explanation of the protocol. At the orientation, the participant could ask any questions they had about the study and they completed a Physical Activity Readiness Questionnaire (PAR-Q) and a health screen questionnaire. At the end of the orientation, the participant was given a 24 h reflection period. After the 24 h of reflection, an informed consent was given to the participant to be reviewed and signed. Upon arrival for their first testing session, each participant reviewed and signed the informed consent.

Each participant for the male and female groups was recruited to fit a medium size clothing ensemble. The measurements employed included a 40” chest, 30” waist, 40” hips, 34” arms and 31.5” inseam for males. For females: 36” chest, 28” waist, 39” hips, 31’ arms and 29” inseam. During the orientation session, each participant took time to ensure the clothing ensemble fit.

The recruited males had a mean age (± SD) of 25 (5) while females had a mean age of 30(8). Males had an average height of 1.80 m (0.07) and an average weight of 77.4 kg (6.7). Females had an average height of 1.69 (0.05) m and an average weight of 64.7 kg (5.4). Seven females were in follicular phase of the menstrual cycle, 2 females were in luteal phase and 1 female had amenorrhea.

A difference in oxygen consumption of 1.3 ml/(kg·min), based on previous pilot studies in the laboratory for metabolic responses to cold environments, was determined to be the difference in means worth detecting. With $\alpha = 0.05$, 80% power and SD = 1 ml/(kg·min) a sample size of 20 total participants (10 males and 10 females) are required to detect biologically important effects. We performed 5 power calculations based on the rectal temperature, mean skin temperature, whole body thermal comfort, heat flux, and oxygen consumption. For rectal temperature, based on pilot study data, it was determined that a difference of 0.3^0C with SD = 0.2^0C would require 7 males and 7 females. For mean skin temperature based on pilot study data, it was determined that a difference of 3.5^0C with SD = 2.5^0C would also require 7 males and 7 females. For thermal comfort, based on pilot study data, it was determined that a thermal comfort difference of 1.0 with SD = 0.5 would require 4 males and 4 females. For heat flux, based on pilot study data, it was determined that a difference of 20W with SD = 15W would require 9 males and 9 females. For cutaneous temperature sensitivity, it was determined that a difference of 0.4^0C and a SD = 0.4^0C would require a sample size of 5 males and 5 females. All sample size justification calculations were set at an $\alpha = 0.05$, 80% power. Oxygen consumption sample size determination was selected as it required the most participants. A summary of the sample size justification can be seen in Table 2.1.

2.2.3. Instrumentation

Metabolic and Ventilation Variables

During each testing session, each participant wore a nose clip and breathed through mouthpiece. The mouthpiece was connected to a Hans-Rudolph non-rebreathing valve which moved expired air to a 3.8 cm diameter tube and subsequently to a mixing box. The Hans-Rudolph non-rebreathing connected also a two-way mass flow sensor (Sensormedics, Yorba Linda, CA, USA). Analysis of fractions of O_2 and CO_2 in expired gases in the mixing box and data collection was performed by gas analysers in a breath-by-breath metabolic cart (Vmax 299c, Sensormedics, Yorba Linda, CA, USA). The inspiratory and expiratory gas flow rates were assessed by the mass flow sensor.

The mass flow sensor was calibrated for volume using a 3L syringe. The metabolic cart gas analysers were calibrated using two calibration gas tanks one with a composition of 26% O_2, balance N_2 and the other 16% O_2, 4% CO_2 and balanced N_2. All calibrations were done at room temperature.

Skin and Core Temperature and Surface Heat Flux

Skin temperature and surface heat flux were detected at seven sites using thermocouples for skin temperature and surface heat flux disks for heat flux (Thermonetics, California USA). The seven sites for skin temperature and surface heat flux were measured on the upper back (T_{UB} & HF_{UB}), lower back (T_{LB} & H_{LB}), chest (T_{CH} & HF_{CH}), abdomen (T_{AB} & HF_{AB}), upper arm (T_{UA} & HF_{UA}) and lower arm (T_{LA} & HF_{LA}). Heat flux discs and skin thermocouples were attached at the seven sites using hypoallergenic tape (Transpore, 3M, St. Paul, MN, USA) (Figure 2.1.). Mean skin temperature was calculated using the unweighted mean of the seven measured sites. Similarly, mean heat flux was determined using the unweighted mean of the seven measured sites. Thermocouples used in skin temperature measurements were calibrated using a temperature controlled water bath (VWR Int, Model 1196, West Chester, Penn USA) in which the temperature was monitored by a traceable platinum thermometer (Fisher Scientific, Nepean, ON, Canada). Heat flux disks were calibrated using a copper encased temperature controlled water bath (VWR Int, Model 1196, West Chester, Penn USA).

Core temperature was measured using a rectal thermistor (DeRoyal TN, USA). The rectal thermistor was 30 cm in length and was inserted 10 cm past the external rectal sphincter. Prior to testing, the rectal thermistors were calibrated in a temperature controlled water bath (VWR Int, Model 1196, West Chester, Penn

USA) while being monitored by a traceable platinum thermometer (Fisher Scientific, Nepean, ON, Canada).

Thermal Comfort

Thermal comfort ratings were assessed using a scale developed by Havenith (35). The comfort rating scale began with 2 being ‘comfortable warm’ and -10 at the lowest end of the scale being ‘extremely cold’ (Figure 2.2). Thermal comfort was assessed at the seven sites at which skin temperature thermocouples and surface heat flux were located: upper back, lower back, chest, abdomen, upper arm, posterior shoulder, lower arm. As well, overall thermal comfort was assessed for the individual at each measurement time point.

.

Clothing Ensemble

Each participant will wear standardized clothing ensembles consisting of outerwear pants, long johns, base layer undershirt, gloves, goggles, face mask, toque, and boots (Mountain Equipment Co-op, Vancouver, BC, Canada). Additionally, volunteers wore either a non-elasticized (NE) or elasticized (E) version of a polyester outerwear jacket (Mountain Equipment Co-op, Vancouver, BC, Canada) for one of their two testing days. The outerwear jackets were non-wicking, non-waterproof with a thermal insulation of 1.656 clo and air permeability of 0.004 $m^3 \cdot s^{-1} \cdot m^{-2}$. The E coats utilized a ‘box baffle’ design which prevented air and coat material from shifting so as to minimize clothing ventilation. The clothing ensembles were all medium in size with the following measurements: 40” chest, 30” waist, 40” hips, 34” arms and 31.5” inseam for males. For females: 36” chest, 28” waist, 39” hips, 31’ arms and 29” inseam. The clothing ensemble over top of the skin temperature thermocouples and heat flux disc and will be worn prior to entering the cold chamber.

2.2.4. Data Acquisition

Skin temperature and surface heat flux were collected using a skin temperature and heat flux transducer discs (Thermonetics, California, USA). The heat flux disc use two thermocouples monitoring the temperature gradient to determine heat flow direction and magnitude, which were sampled at a rate of 40 Hz and recorded every 20 s connected to a data acquisition system connected to a computer running LabVIEW software (Ver. 7.1, National Instruments, Austin, TX, USA). Similarly core temperature was recorded using a thermistor connected to a data acquisition system connected to a computer running LabVIEW software (Ver. 7.1, National Instruments, Austin, TX, USA). Additionally, all physiological data was recorded periodically every 3 minutes by hand on data sheets and kept in a binder.

. Thermal comfort ratings were collected by hand and recorded on data sheets every 3 min prior to and during trials in the climatic chamber All data sheets were then transferred to a spreadsheet on a computer and data sheets were stored in a binder.

2.2.5. Protocol

Each participant had two trials on separate days with one trial for each outerwear jacket. Females were tested on successive days to avoid confounding results due to the menstrual cycle. After instrumentation, each volunteer wore one of the two jackets and sat at rest for 5 min outside of the climatic chamber at room temperature, this was called Warm Sitting Rest (WRS). Following the initial rest, each participant entered the climatic chamber set at -8^{0}C (Tenney Engineering Inc., Union, NJ, USA). For the first 5 min in the chamber the participant was in the Cold Rest while Upright (CRU). Next, the participant walked at 5 km/h on the treadmill for 20 min, where the first 10 min of this stage the participant was in the Cold Exercising and Walking (CEW) with no arm movements. During this time a fan was blowing wind at ~10 km/h to simulate walking conditions. After 10 min of walking, each participant began an arm movement involving a pulley system to simulate Nordic skiing conditions or Cold Exercise Walking with Arm movement (CEWA). After the 20 min of exercise, the participant was in Cold Sitting at Rest (CRS) for another 5 min. After the conclusion of CRS, the testing session was complete for that outerwear.

2.2.6. Statistical Analysis

The physiological outcome variables of interest from each volunteer in the climatic chamber testing portion are skin temperature, core temperature, thermal comfort, surface heat flux, oxygen consumption, and heart rate.

The main effect of Sex (Male, Female), Outerwear Jacket (Non-Elasticized, Elasticized) and their interaction (Sex x Outerwear Jacket) were computed and examined using a 2-Factor Mixed Model ANOVA by SPSS software (Version 23, Surrey, UK). Sex was a non-repeated between-subjects factor and Outerwear Jacket was set as the repeated within-subject factor.

Follow-up testing, was with an unpaired t-test to compare the means of either Sex or Outerwear Jacket if a main effect of Sex by Outerwear Jacket were detected in the ANOVA model. Results are to be considered statistically significant if $p<0.05$.

2.3. Results

Comparing sexes divided by coat types, there was no significant difference in mT_{SK} (Figure 2.3) and mHF (Figure 2.4) during all activity states while wearing either NE or E coats. There was a significantly greater T_{RE} of ~0.2°C in females vs. males when wearing NE at all activity levels (Figure 2.5). These differences in T_{RE} responses between the sexes were removed when assessing ΔT_{RE} (Figure 2.6).

Between the sexes wearing either NE or E coat types absolute VO_2 (L/min) was significantly greater in males than females by ~ 0.1 L during CRU, CEW and CEWA ($p<0.05$) for both NE and E coat types (Figure 2.7). When normalizing for weight, there was no sex differences in VO_2 (Figure 2.8). Females had a heart rate response during and/or after exercise that was significantly greater by ~10-15 bpm compared to males in both NE and E coat types (Figure 2.8).

Females in NE coats had a significantly greater mT_{SK} (Figure 2.9) compared to the E coat during CEW ($p<0.05$) and CEWA ($p<0.05$). In the NE coat females had an mT_{SK} 29.5^{0}C (1.1^{0}C) during CEWA while in the E coat mT_{SK} was at 28.9^{0}C (0.89^{0}C). For both males and females between coat types there was no significant difference in T_{RE} (Figure 2.10), ΔT_{RE} (Figure 2.11) and mHF (Figure 2.12) for all activity states. For VO2, there was a significant difference during CEW ($p<0.05$) between coat types for females. While wearing NE coat, females gave a VO_2 of 0.95 L/min (0.12 L/min) compared to a lower response in the E coat which had a VO_2 of 0.84 L/min (0.09 L/min). Men had the same VO_2 response in both coat types (Figure 2.13).

Assessing thermal comfort (TC) at the 7 measured sites and overall, males reported a significantly higher TC during CEWA on UB ($p<0.05$), AB ($p<0.05$), LA ($p<0.05$), UA ($p<0.05$) and overall (OV) ($p<0.05$) in the E coat compared to the NE coat. Males reported a TC_{UB} of -1.0 (1.0), a TC_{AB} of -0.9 (1.5), a TC_{LA} of -1.0 (1.1), a TC_{UA} -0.7 (1.4) and a TC_{OV} -1.4 (1.2) in the NE coat compared to the E coat which reported higher TC_{UB} of -0.2 (1.2), TC_{AB} of -0.2(1.6), TC_{LA} of -0.4 (1.1), TC_{UA} -0.3 (0.9) and TC_{OV} of -0.6 (1.2). There was no significant differences in TC for females at the 7 measured sties and overall.

2.4. Discussion

When sex comparisons were made for the two coat types, there was no physiological differences due to cold stress in skin temperature, change in core temperature and heat flux. Instead, males had greater absolute oxygen consumption rate while wearing both coat types compared to females, and females had a greater heart rate during the exercise protocol compared to males. This suggests that females may have been working at a greater intensity compared to males. It is of note the differences in VO_2 disappeared after values were normalized for body weight differences between sexes. When assessing differences in coat types within each sex, it was revealed that females in the elasticized coats showed a decrease in skin temperature in comparison to the non-elasticized coat during exercise condition. This result was unexpected since the elasticized coat should be greater at trapping more still air in cold conditions and providing greater thermal insulation than the non-elasticised coat. Results indicated that during cold stress females generally had higher rectal temperature~~s~~ supporting that female core temperature remains elevated compared to men during cold stress.

For thermal comfort our results show that there were advantages for the elasticized coat compared to a non-elasticized coat for males during exercise with arm movement. The results indicate, at least for males, that successful design of an elasticized clothing garment with box baffles can provide greater regional and overall thermal comfort when compared to a non-elasticized version.

With respect to skin temperature and heat flux sex differences in the cold, our results are not entirely the same as that reported in the literature (8, 75, 82, 85). Burse, and other experts in the field indicated that females will often have lower skin temperatures during cold exposure due to a greater vasoconstriction (8, 55). While this was not revealed in our results, this may be due to difference in experimental protocol. In our study, we utilized the cold weather clothing to aid in maintenance thermal balance. This supports that proper utilization of technical apparel for cold weather conditions can alleviate the strong vasoconstriction cold responses in skin temperature seen in females. A higher core temperature in females compared to males for exercise in the cold is consistent with the literature (6, 10, 50, 57, 79). The difference seen in core temperature might be attributed to the effects of the menstrual cycle. In females, there is an increase in core temperature of about 0.3 to 0.6^{0}C following ovulation during the luteal phase compared to the follicular phase (10, 79). In this study, however, 7 of 10 females were in the follicular phase and one was had amenorrhea that speaks against this view.

Our results showed no difference for skin temperature in males between coat types indicative of no difference in heat retention by either of the coats in cold weather conditions. For females, the elasticized coat was less effective at maintaining skin temperatures compared to the non-elasticized coats. The reason for this difference for females remains to be resolved in a future study. Females typically display a more pronounced vasoconstriction of the periphery compared to males which may contribute to this explanation (8, 55).

Some limitations arose during thermal comfort assessment. It may be advantageous in future studies utilizing Havenith et al.’s thermal comfort scale to use a continuous scale for thermal comfort instead of whole integers used in this study. This would provide greater resolution when performing analysis of thermal comfort and may provide less variation in reported comfort ratings. Future studies employ a greater difference in clothing ventilation through the construction of the clothing ensemble to further emphasize the potential thermoregulatory effects of trapping still air in the microenvironment. As well as sweat rates could be compared between sexes as another potential course or variation contributing to these outcomes. Secondly, as seen in sex differences in oxygen consumption and heart rate, it seems that the work load given by the treadmill speed should be standardize to control for these variables. To ensure that all participants are working at the same workload, it would best to improve this methodology by performing a VO_2 max test for each volunteer prior to cold stress to set their work rates as a percentage of their maximum VO_2. This would provide greater insight when comparing male and female physiology as well as clothing physiology.

Conclusion

It was hypothesized that for the same cold conditions and same light intensity of exercise, males and females in each coat type would have similar core temperature, oxygen consumption rate, and heart rates plus that females vs. males would have lower skin temperature and surface heat flux. Our results did not have the hypothesized outcomes, absolute oxygen consumption rate and metabolic heat release were greater in males than females whereas heart rate were significantly greater in females compared to males. Skin temperatures and heat flux were not different between the sexes. It was hypothesized that an elasticized coat will give a diminished physiological strain to cold stress than a non-elasticized coat. Our results were not in agreement with this hypothesis, as females had a significantly lower skin temperature when wearing an elasticized coat compared to a non-elasticized coat. Finally it was hypothesized that an elasticized coat would give a better regional and overall thermal comfort relative to that of a non-elasticized coat. For males, our results were in agreement with our hypothesis as males reported significantly greater thermal comfort at multiple sites and overall during cold during exercise with arm movement while wearing an elasticized coat compared to a non-elasticized coat whereas females had no differences in thermal comfort between the two coat types.

2.5. Tables

Table 2.1 **Sample size justification of the different physiological variables. α-level was set at 0.05 and power was set at 0.80.**

Outcome Variable	Difference in Means Worth Detecting	Standard Deviation	Number of Participants
Rectal Temperature	0.3°C	0.2°C	7 males, 7 females
Mean skin Temperature	3.5°C	2.5°C	7 males, 7 females
Whole body Thermal Comfort	1.0	0.5	4 males, 4 females
Mean Surface Heat flux	20 W	15 W	9 males, 9 females
Cutaneous Temperature Sensitivity	0.4°C	0.4°C	5 males, 5 females
Oxygen Consumption	1.3 ml/(kg·min)	1 ml/(kg·min)	10 males, 10 females

From data collected in a December 2014 MEC pilot study

Table 2.2 **Table of characteristics for both male and female participants; values are the mean ±SD.**

Participant	Sex	Height (m)	Weight (kg)	BMI (kg m^{-2})	Age (y)
#1	Male	1.79	77.9	21.3	22
#2	Male	1.81	72.2	22.0	22
#3	Male	1.85	76.2	22.3	22
#4	Male	1.89	85.2	23.6	23
#5	Male	1.75	68.9	22.5	32
#6	Male	1.82	72.1	21.5	23
#7	Male	1.63	81.2	30.6	29
#8	Male	1.86	83.9	24.3	24
#9	Male	1.79	87.3	27.3	36
#10	Male	1.78	69.1	21.8	25
#11	Female	1.66	58.9	21.2	28
#12	Female	1.75	69.9	22.8	29
#13	Female	1.65	65.5	24.0	19
#14	Female	1.68	70.6	24.7	44
#15	Female	1.62	57.3	21.7	23
#16	Female	1.71	59.8	20.3	21
#17	Female	1.68	72.8	25.8	37
#18	Female	1.68	61.2	21.7	28
#19	Female	1.79	66.1	20.6	40
#20	Female	1.69	66.6	23.0	34
Mean	Male	1.79 (0.07)	77.4 (6.7)	24.0 (2.8)	25 (5)
Mean	Female	1.69 (0.04)	64.8 (5.4)	22.6 (1.8)	30 (8)
	p-values	0.001	<0.001	0.16	0.203

2.6. Figures

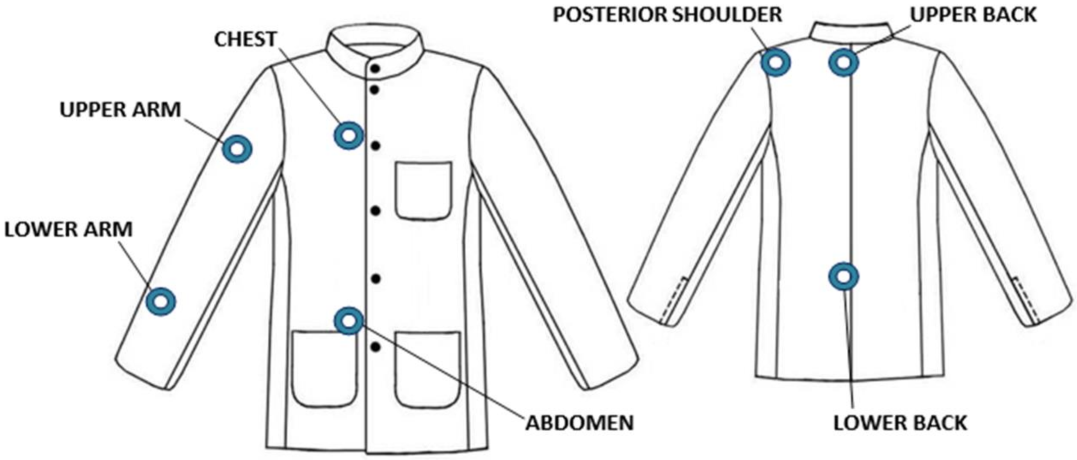


Figure 2.1 Seven sites of skin temperature thermocouples, heat flux discs and thermal comfort location.

Figure 2.2 Thermal comfort rating scale used in thermal comfort assessment from Havenith et al. (1992).

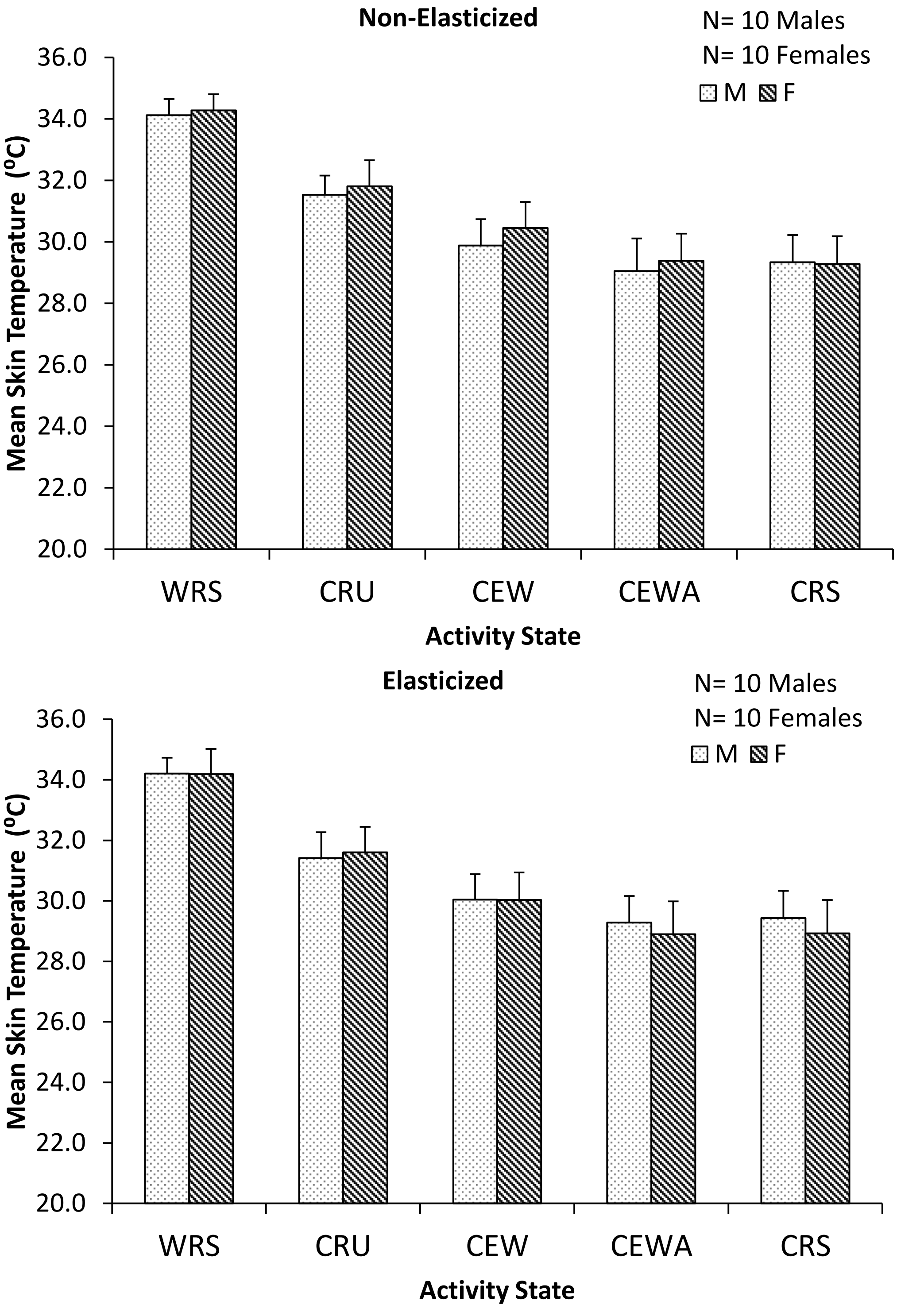


Figure 2.3 Mean skin temperature response for both NE and E winter coats.

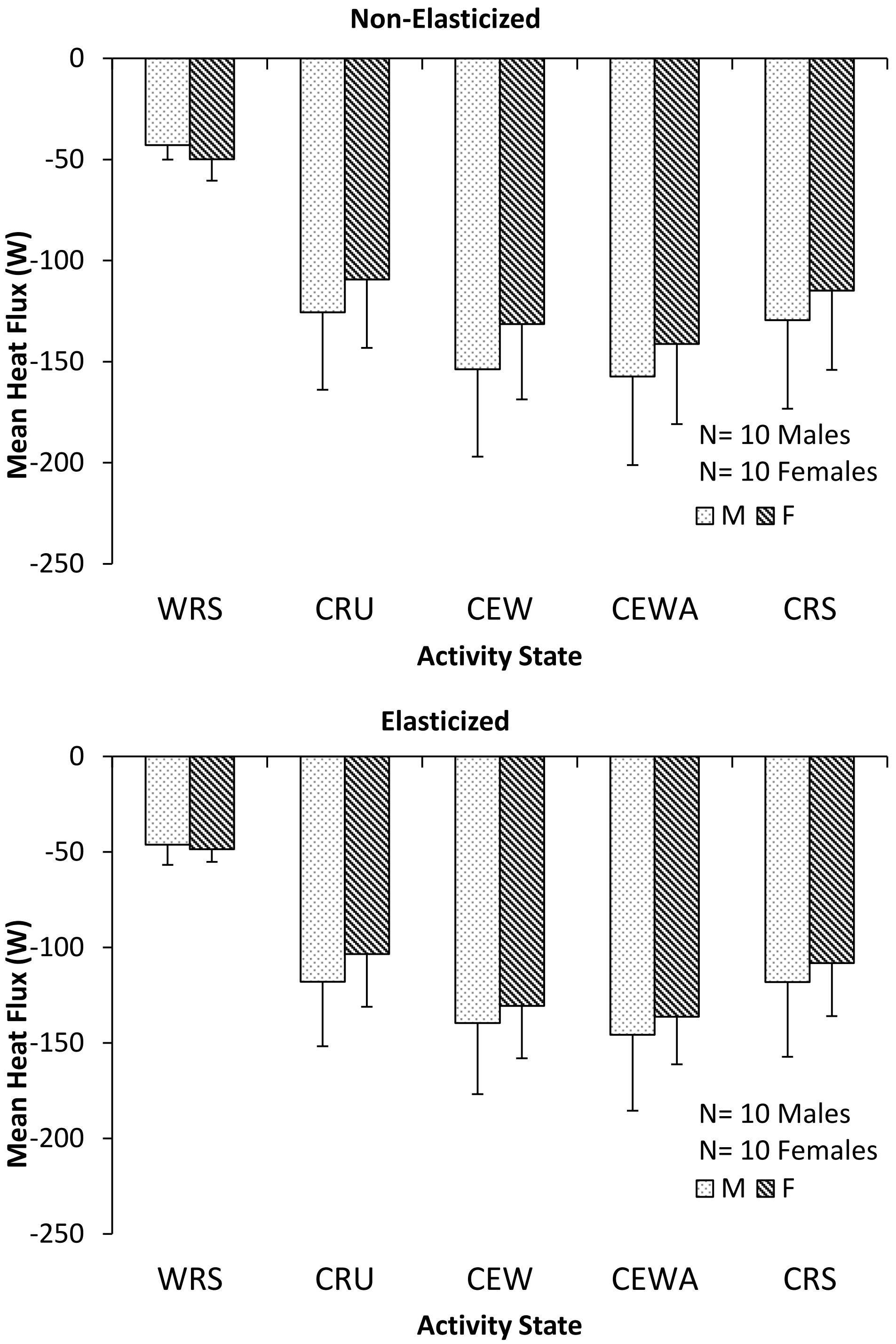


Figure 2.4 Mean heat flux response for both NE and E winter coats

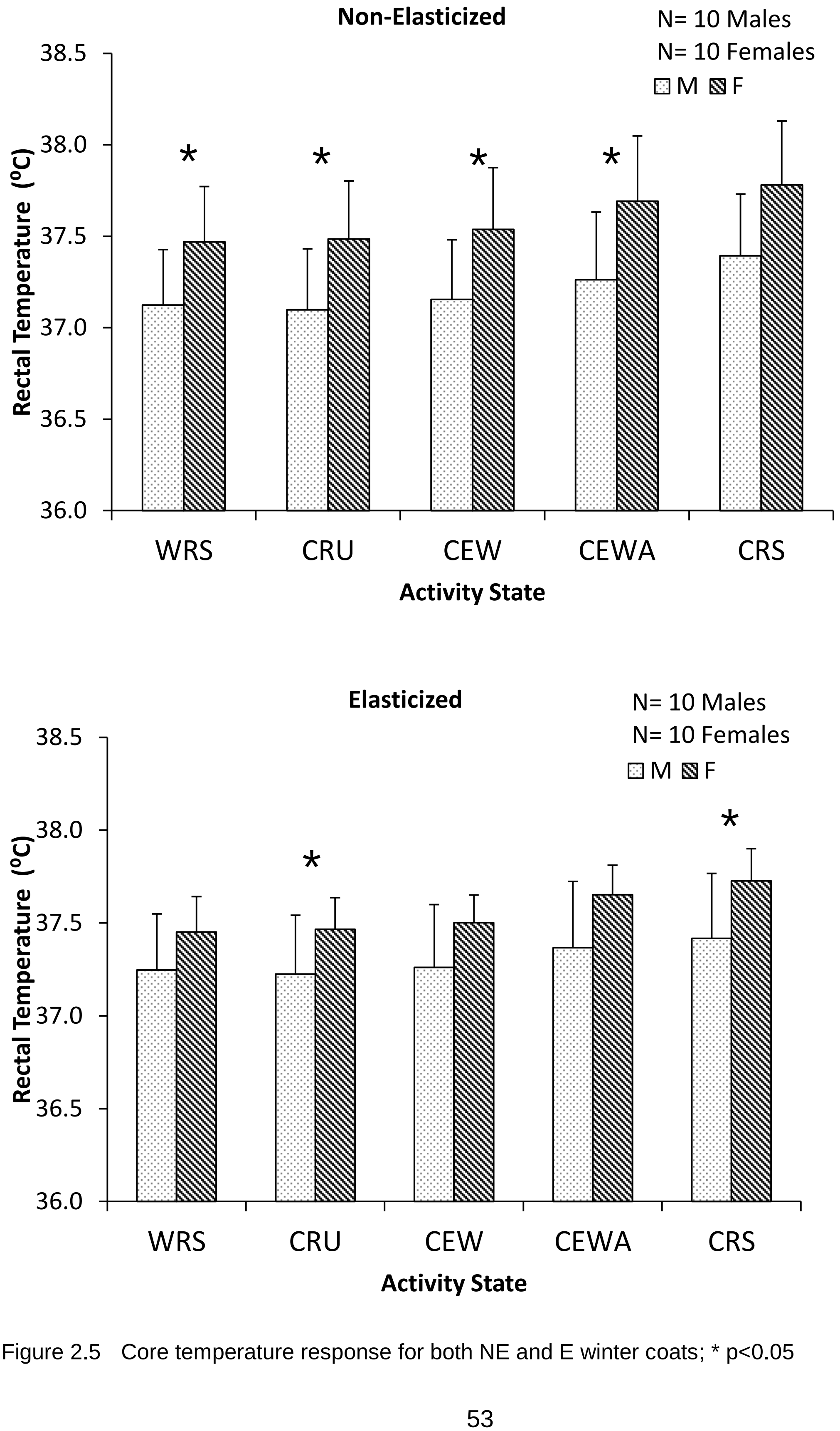


Figure 2.5 Core temperature response for both NE and E winter coats; * $p<0.05$

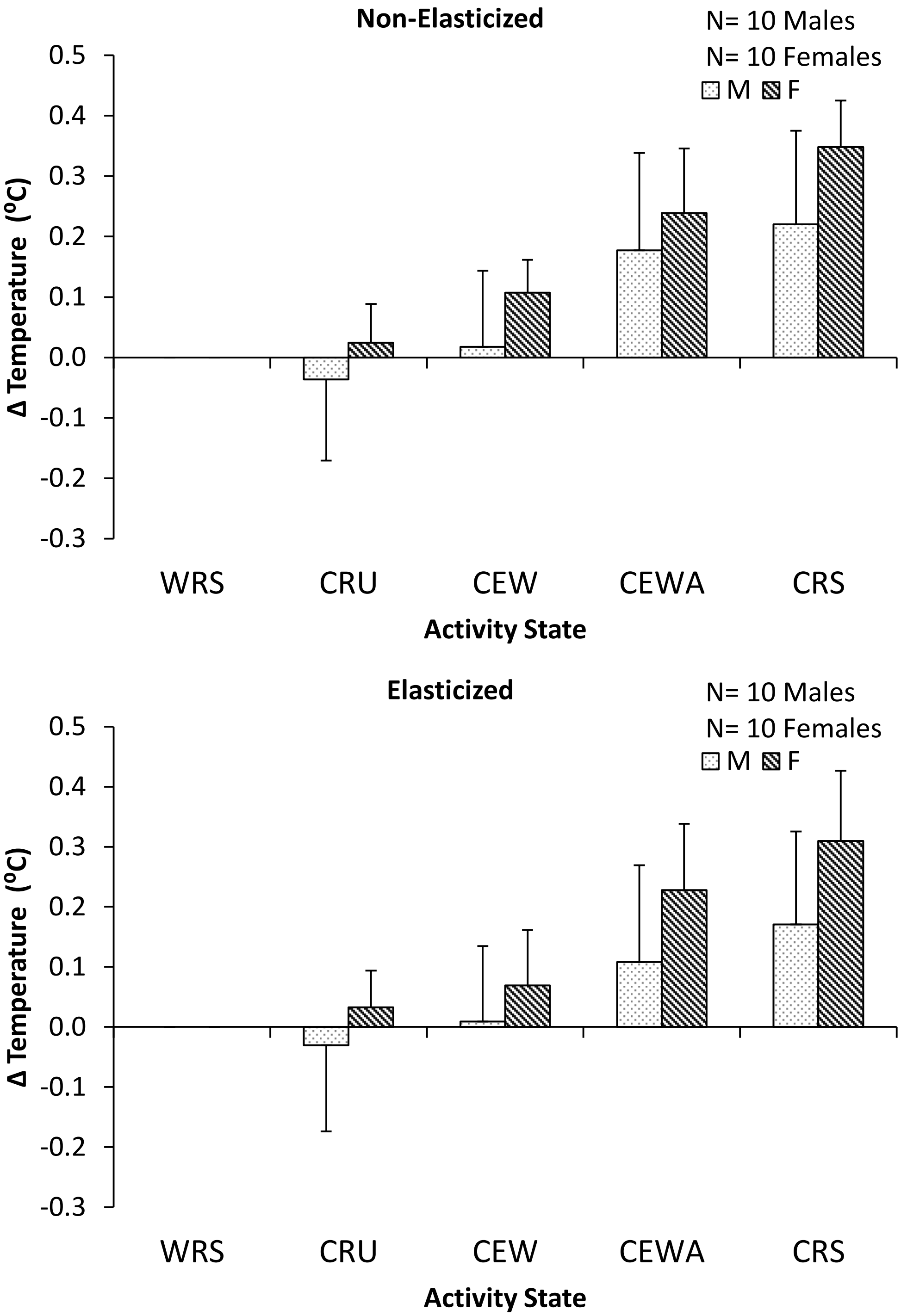


Figure 2.6 Δ Core temperature response for both NE and E winter coats

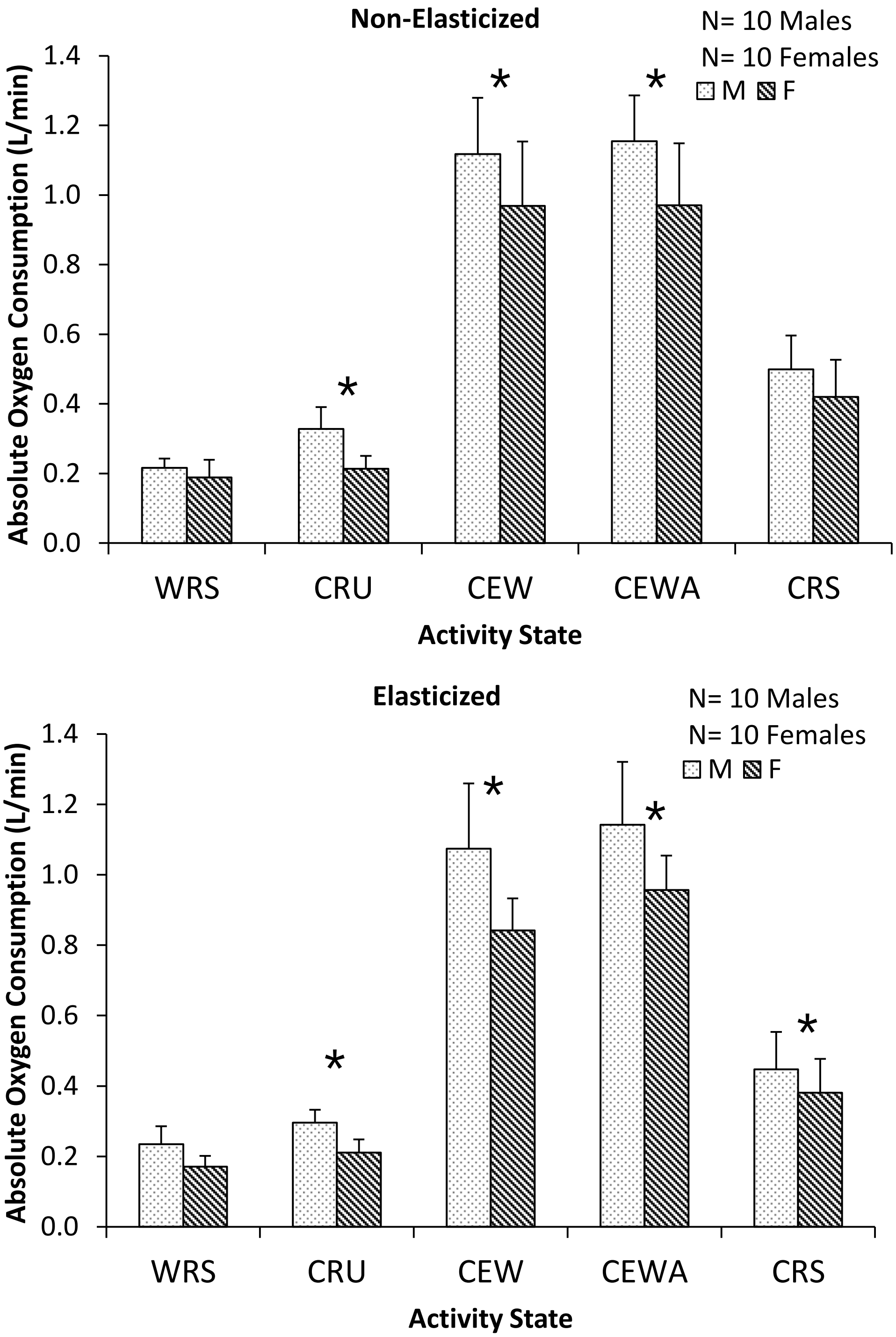


Figure 2.7 Absolute oxygen consumption response for both NE and E winter coats; * $p<0.05$

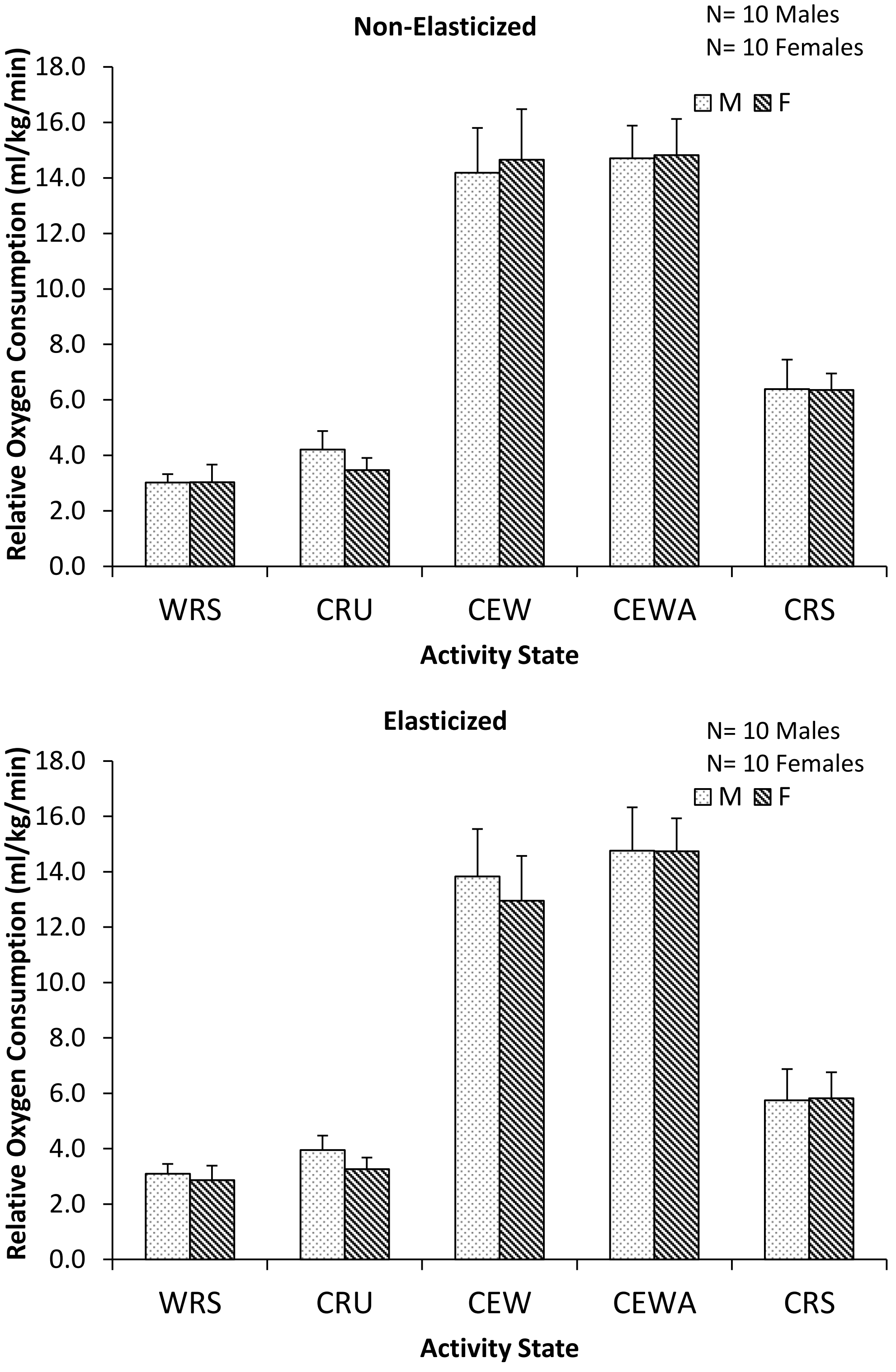


Figure 2.8 Relative oxygen consumption response for both NE and E winter coats

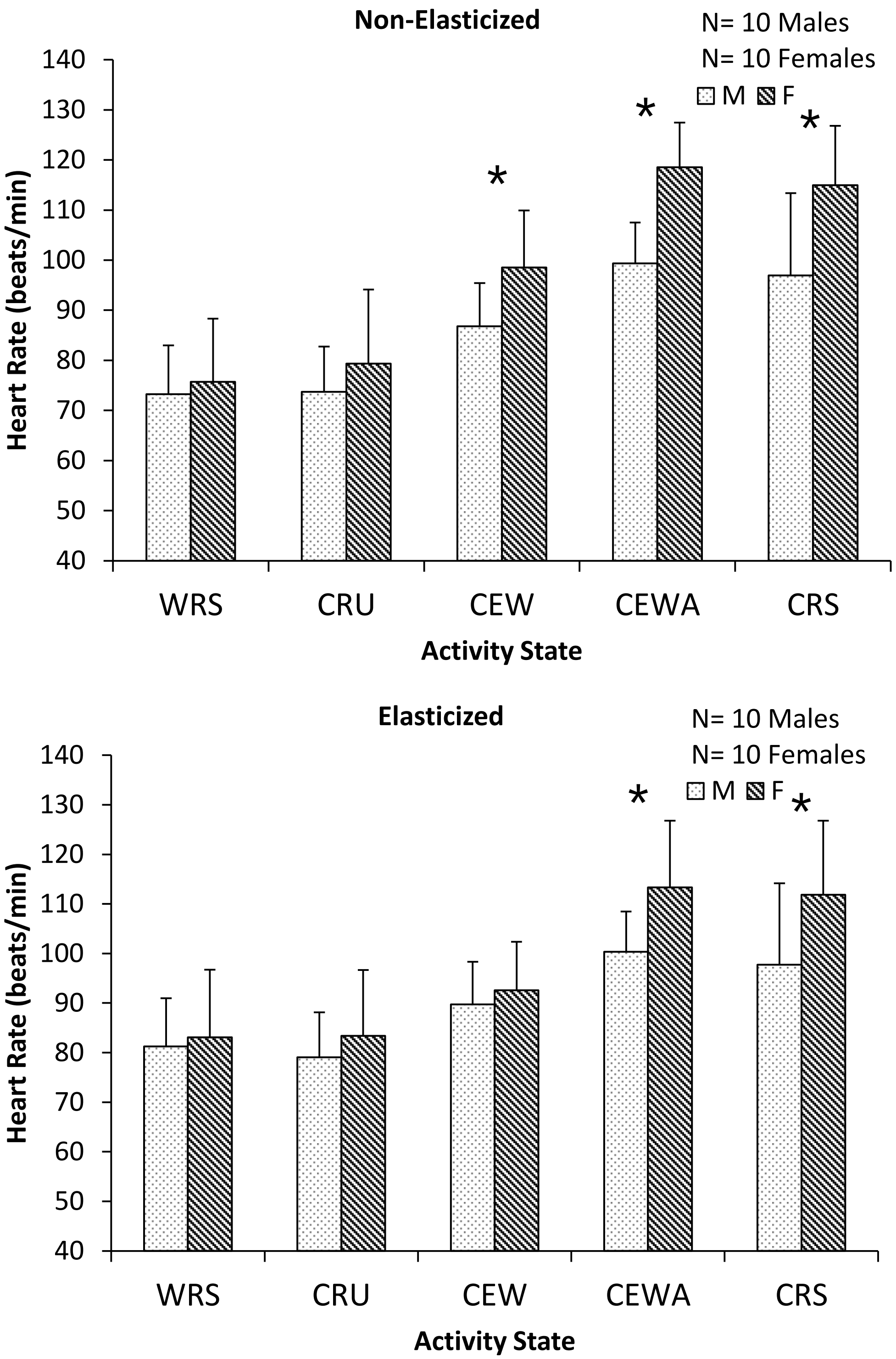


Figure 2.9 Heart rate response for both NE and E winter coats; * $p<0.05$

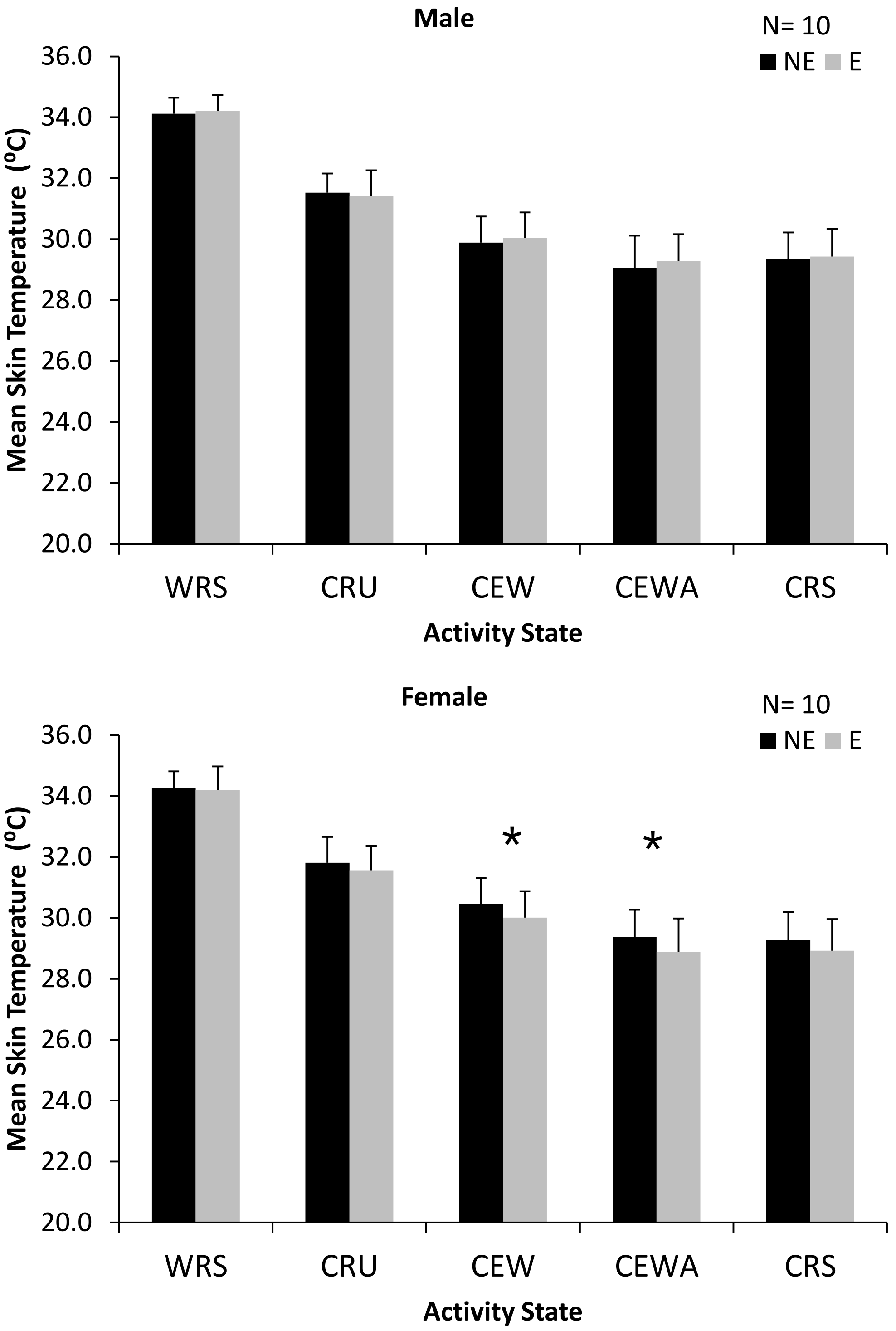


Figure 2.10 Mean skin temperature response between males and females divided by non-elasticized coat and elasticized coat; * $p<0.05$

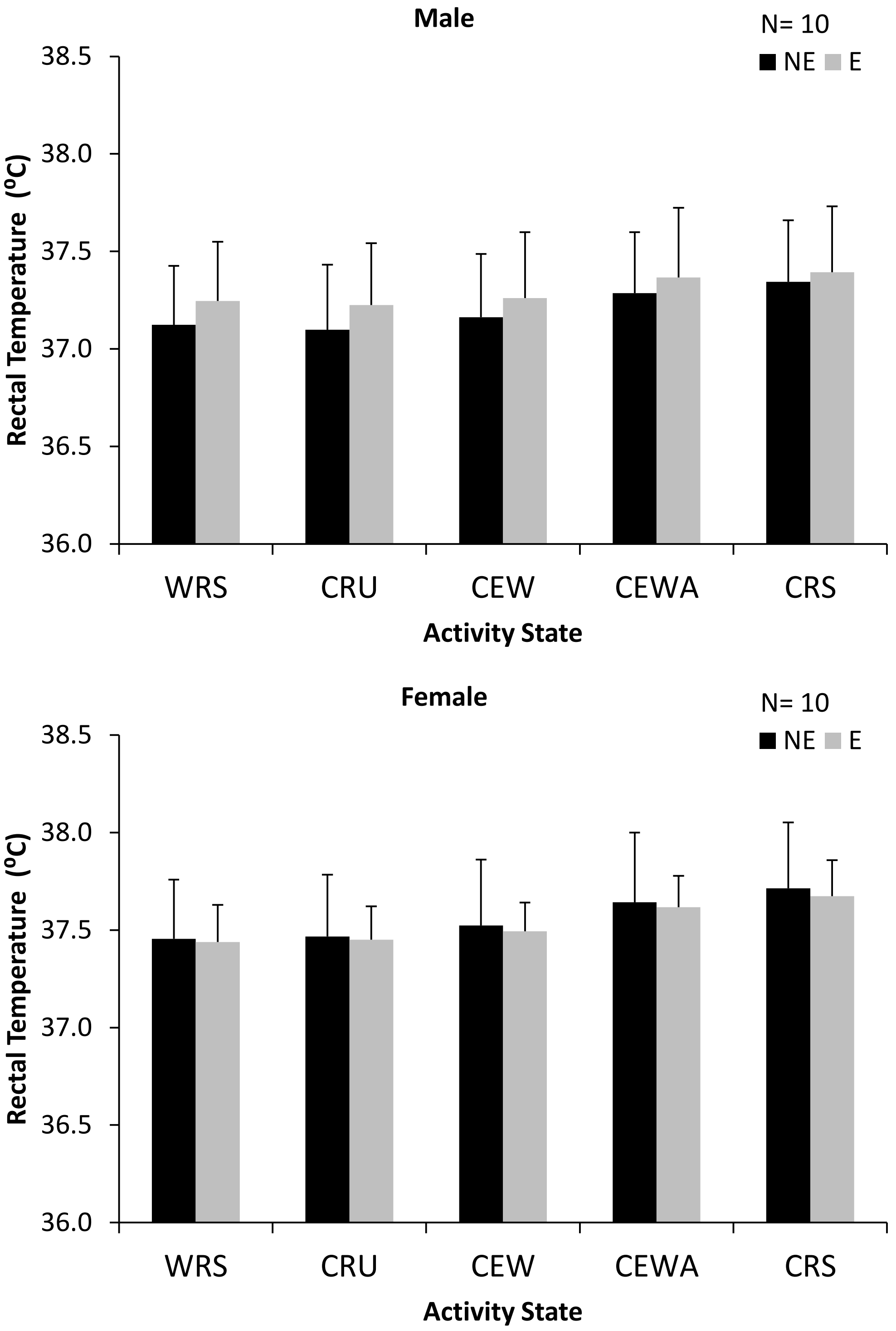


Figure 2.11 Rectal temperature response between males and females divided by non-elasticized coat and elasticized coat

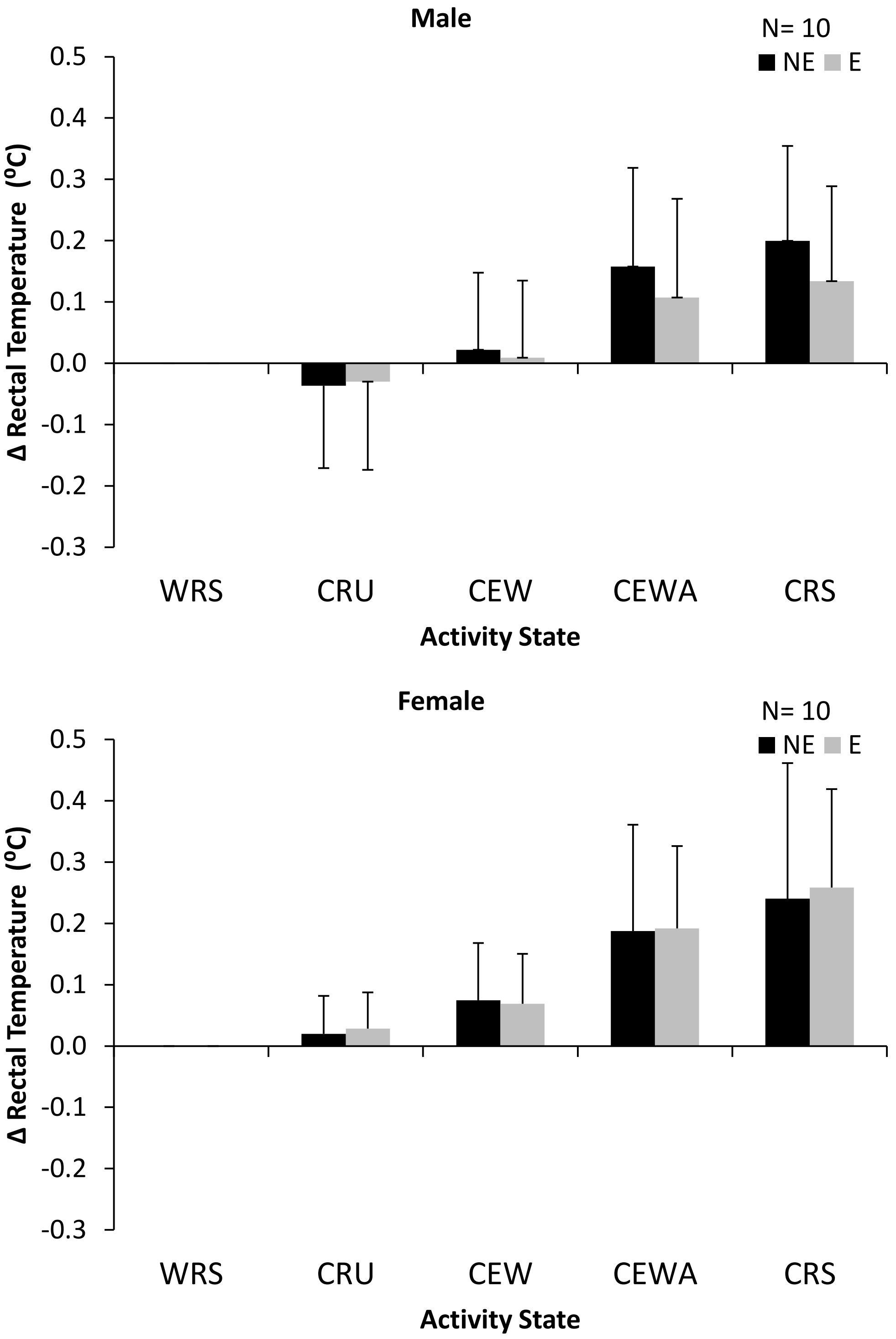


Figure 2.12 Change in rectal temperature response between males and females divided by non-elasticized coat and elasticized coat

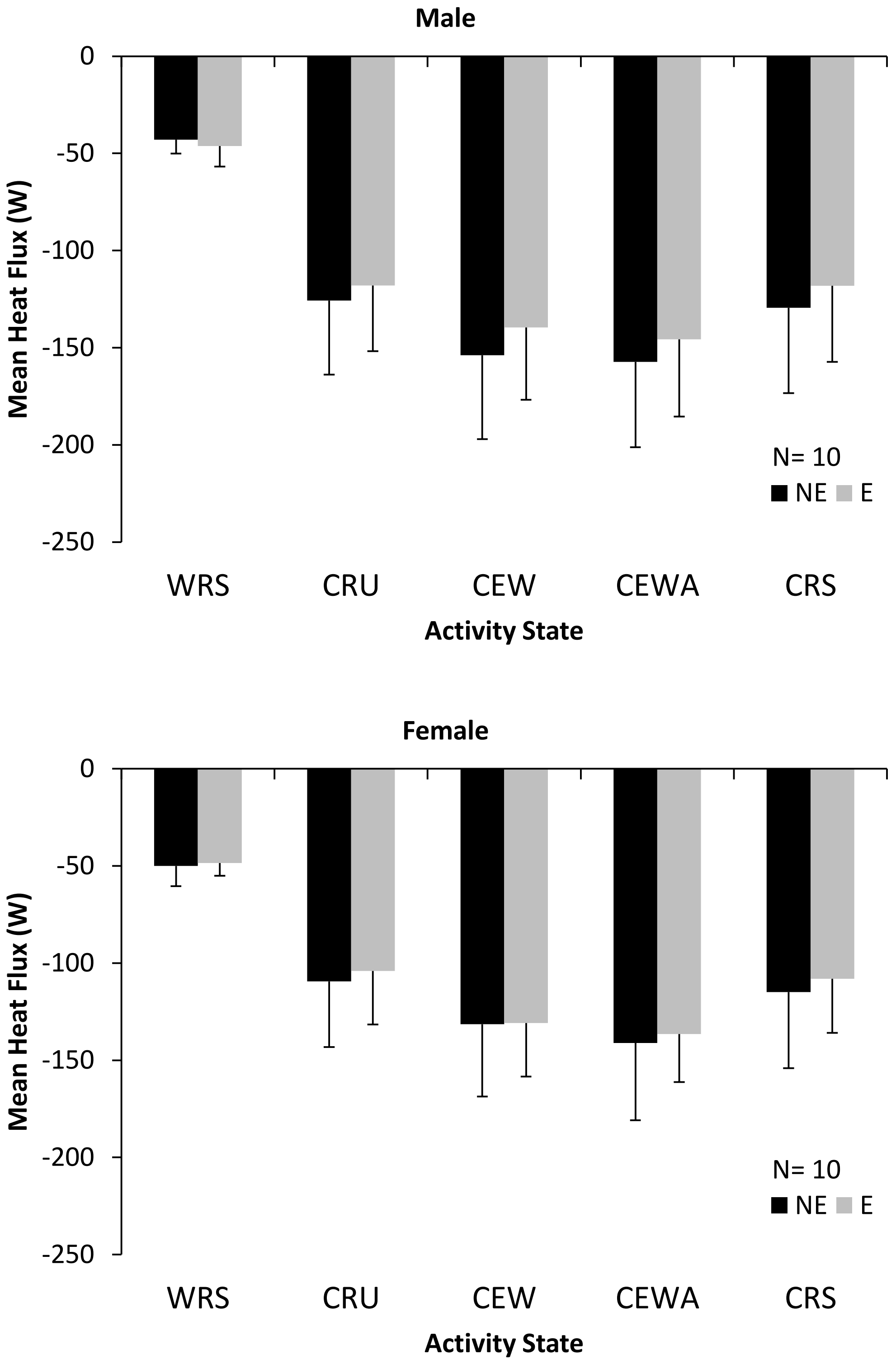


Figure 2.13 Mean heat flux response between males and females divided by non-elasticized coat and elasticized coat

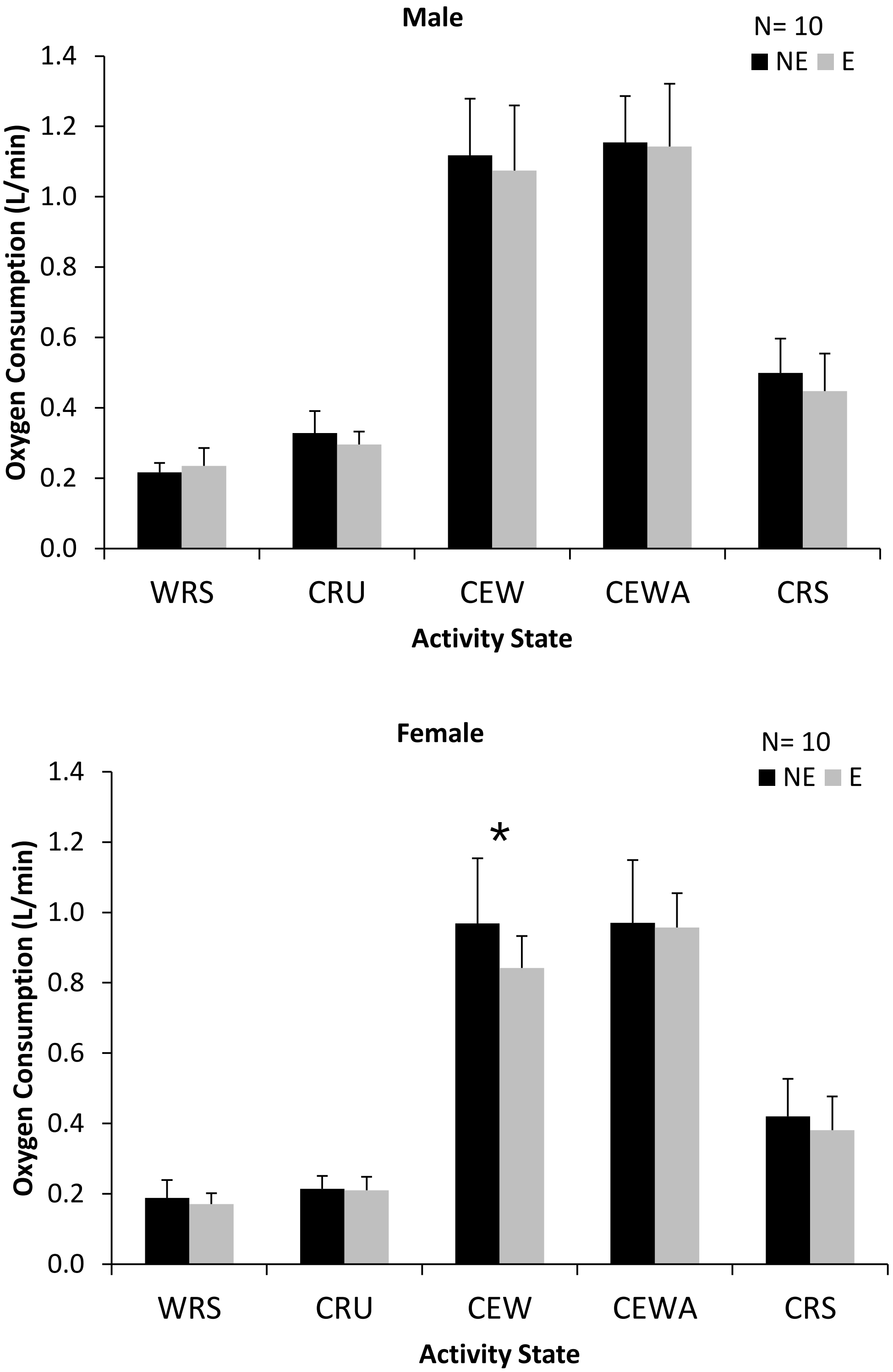


Figure 2.14 Oxygen consumption between males and females divided by non-elasticized coat and elasticized coat; * $p<0.05$

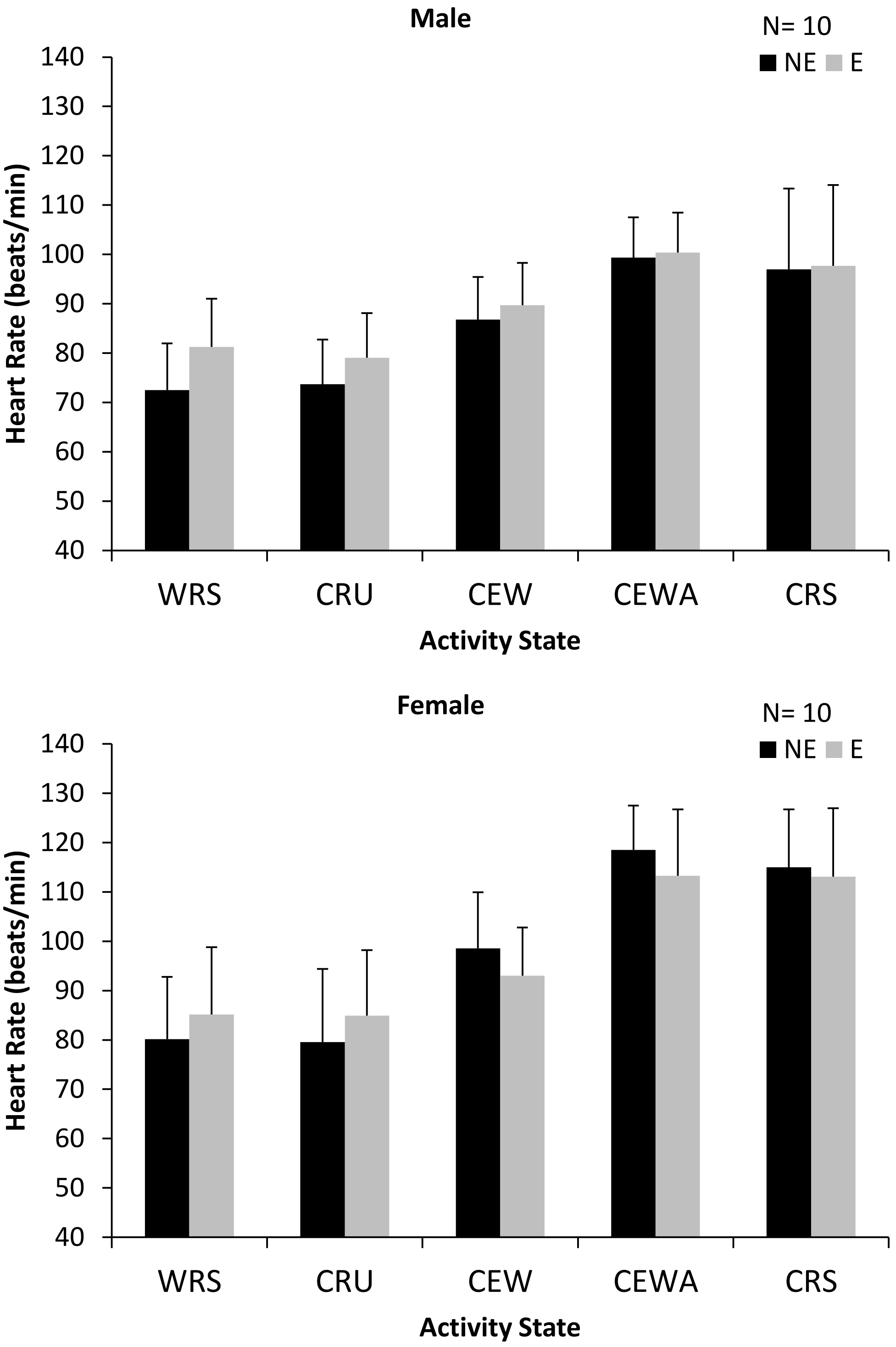


Figure 2.15 Heart rate between males and females divided by non-elasticized coat and elasticized coat

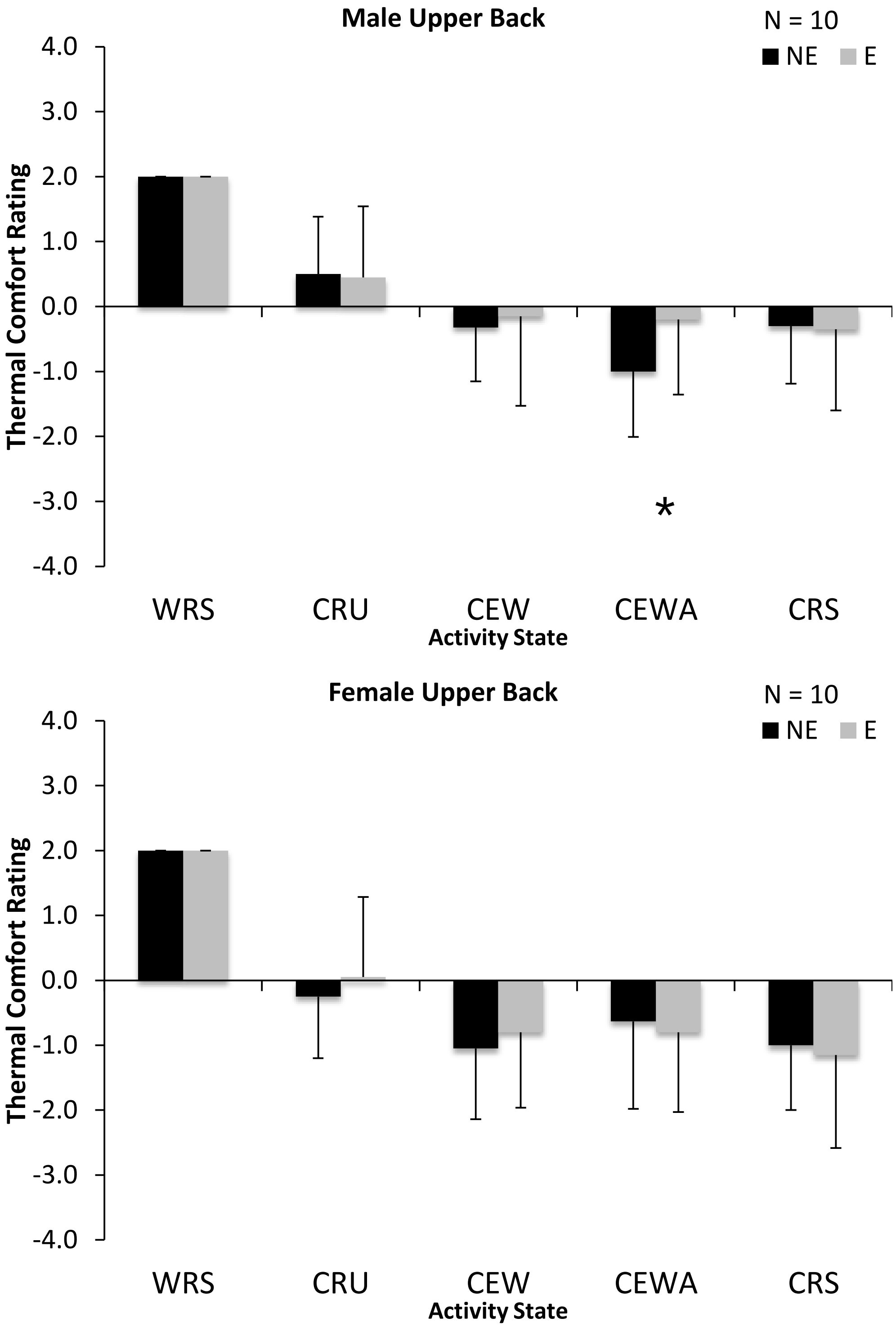


Figure 2.16 Upper back thermal comfort (TC_{UB}) comparing both NE and E coat for males and females; * $p<0.05$

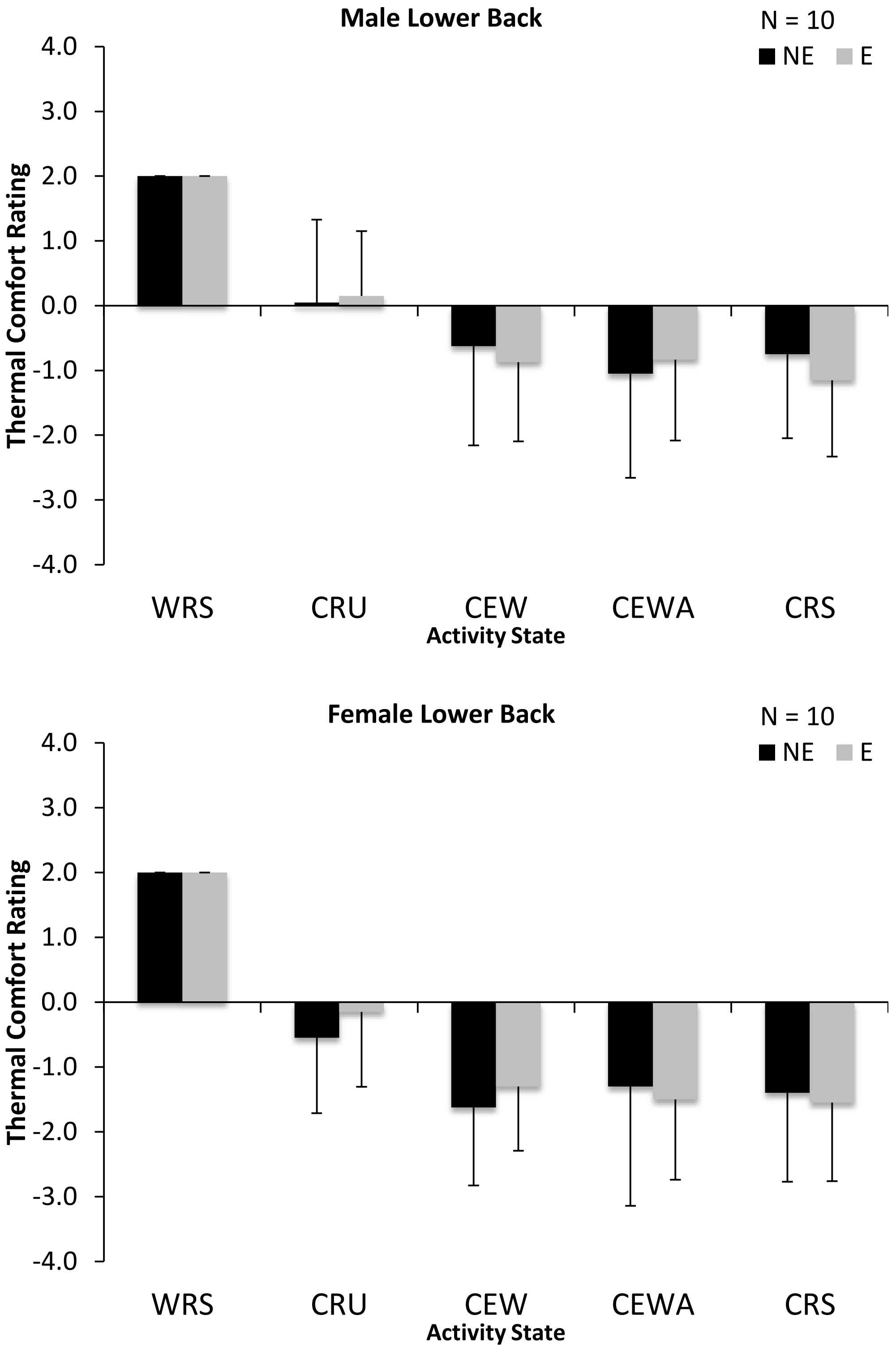


Figure 2.17 Lower back thermal comfort (TC_{LB}) comparing both NE and E coat for males and females

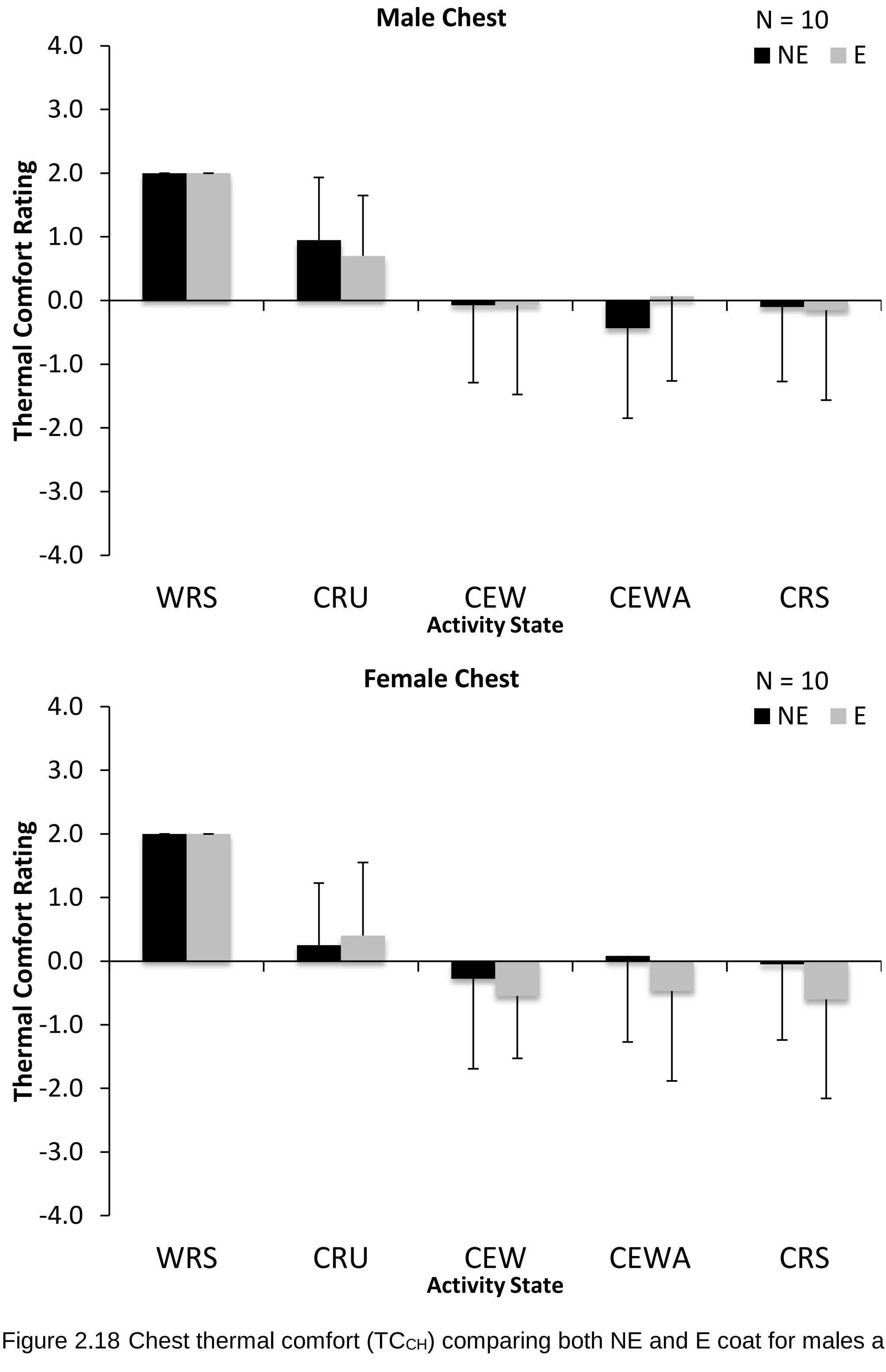


Figure 2.18 Chest thermal comfort (TC_{CH}) comparing both NE and E coat for males and females

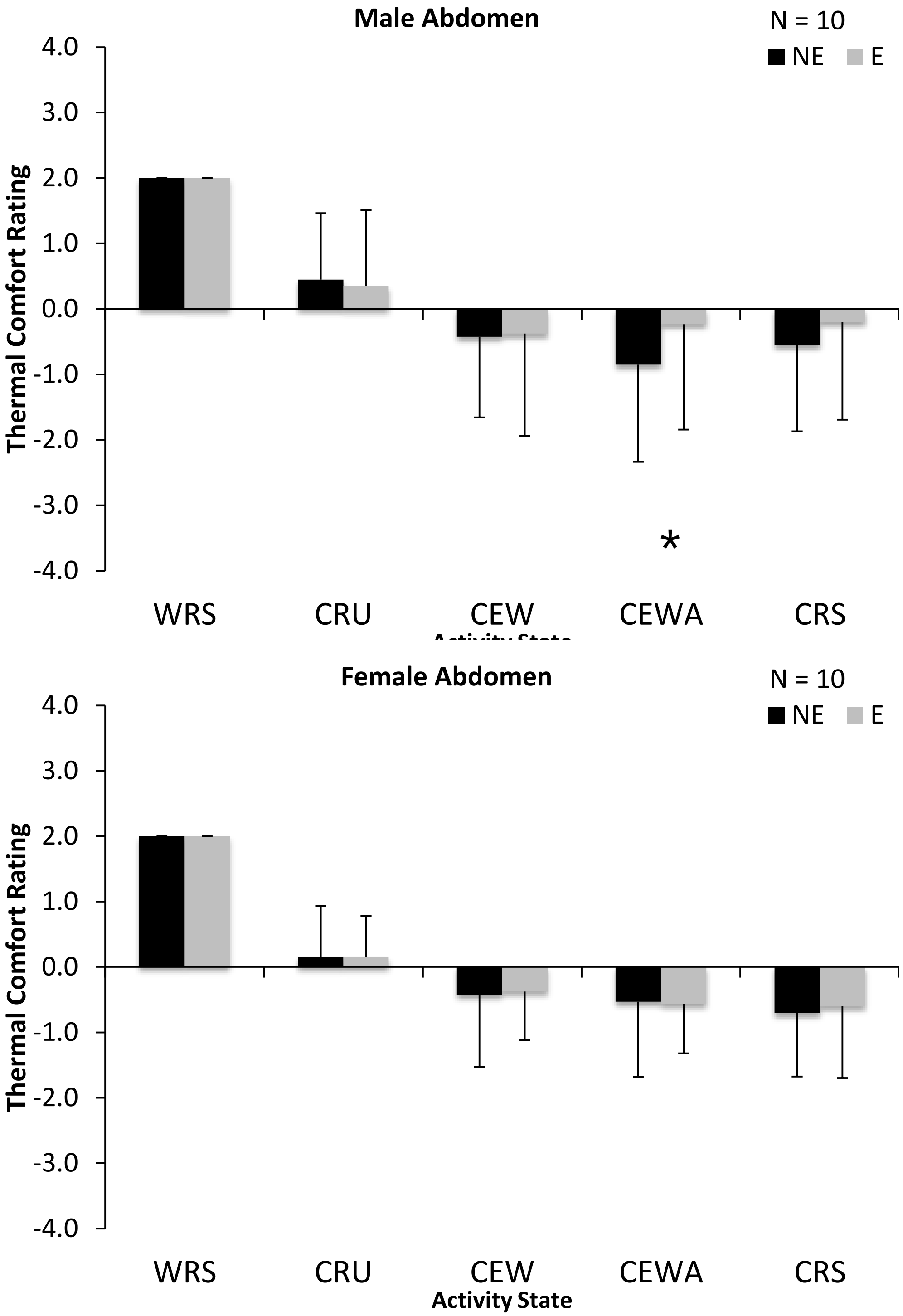


Figure 2.19 Abdomen thermal comfort (TC_{AB}) comparing both NE and E coat for males and females; * $p<0.05$

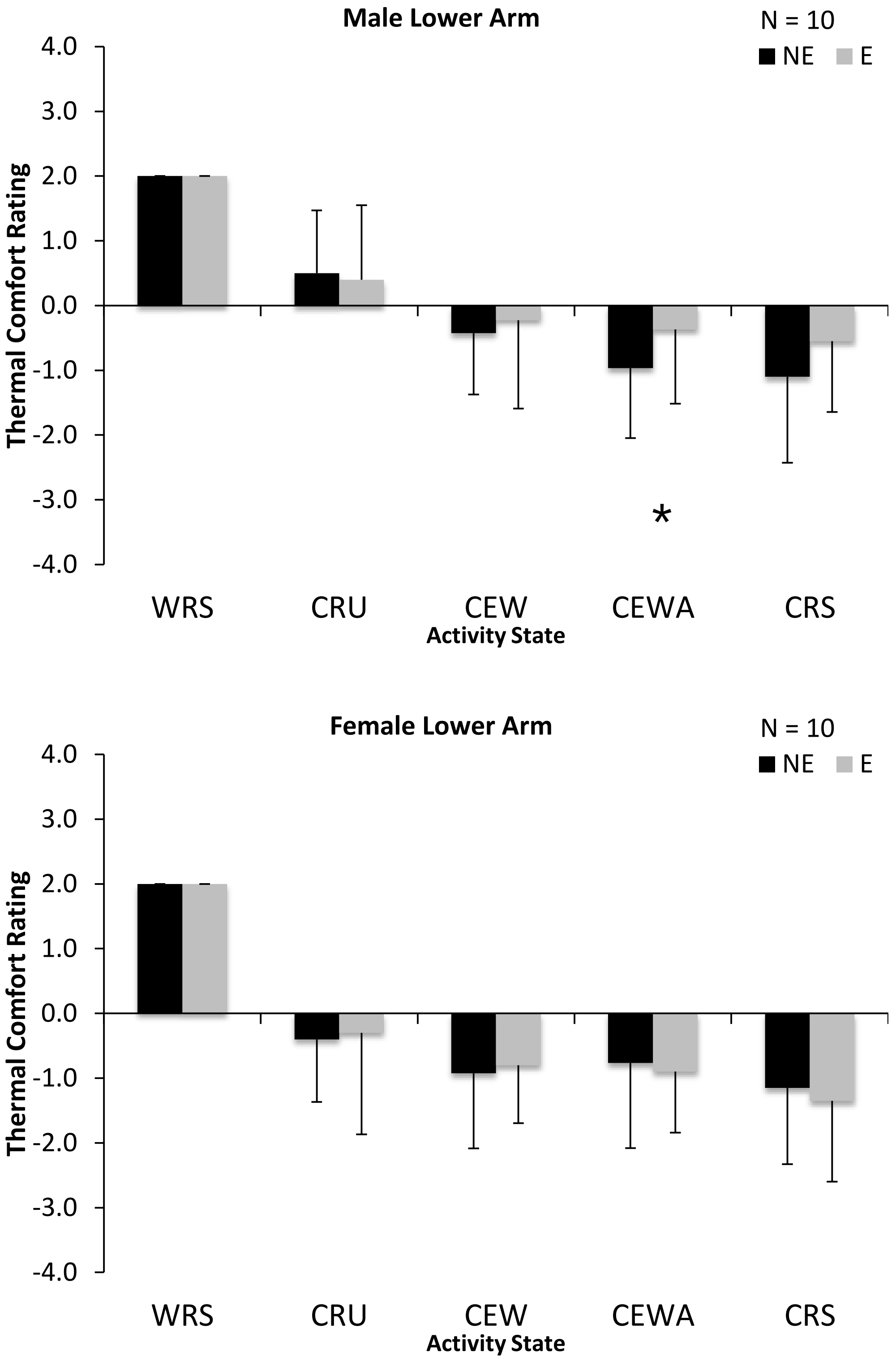
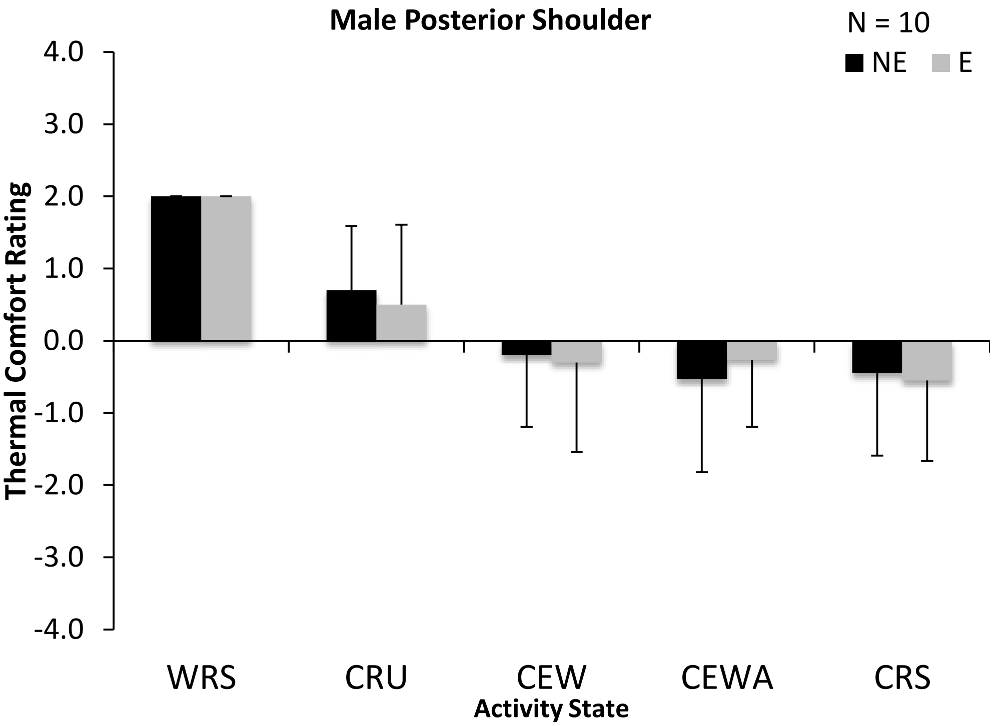


Figure 2.20 Lower Arm thermal comfort (TC_{LA}) comparing both NE and E coat for males and females; * $p<0.05$



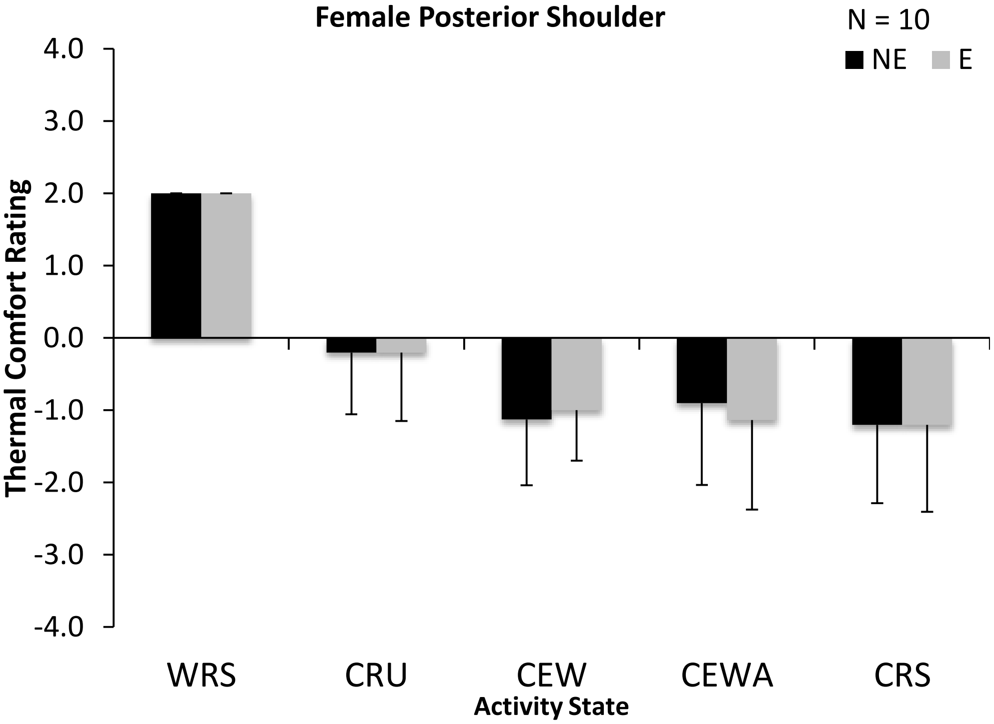


Figure 2.21 Posterior shoulder thermal comfort (TC_{PS}) comparing both NE and E coat for males and females

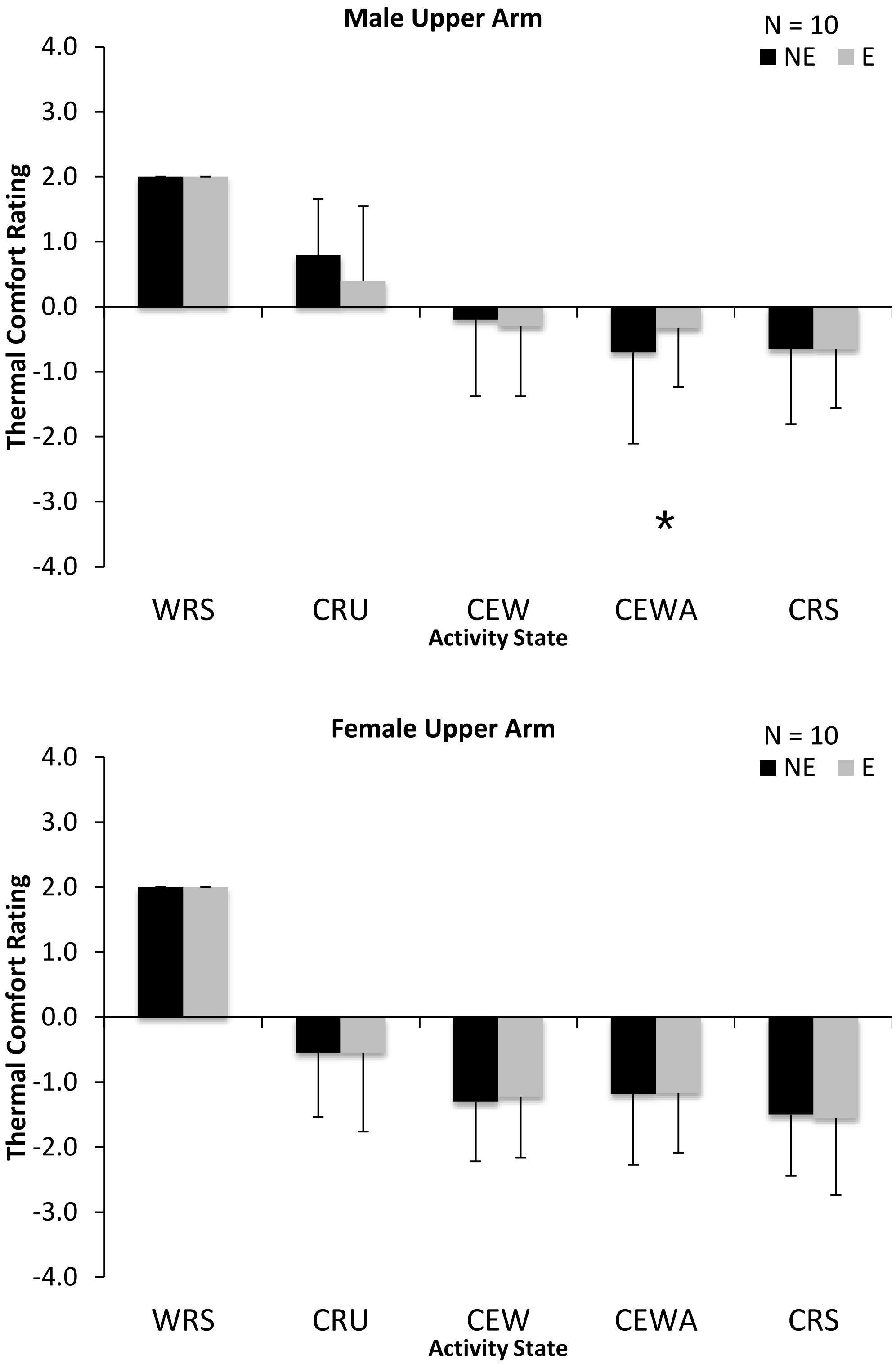


Figure 2.22 Upper arm thermal comfort (TC_{UA}) comparing both NE and E coat for males and females; * $p<0.05$

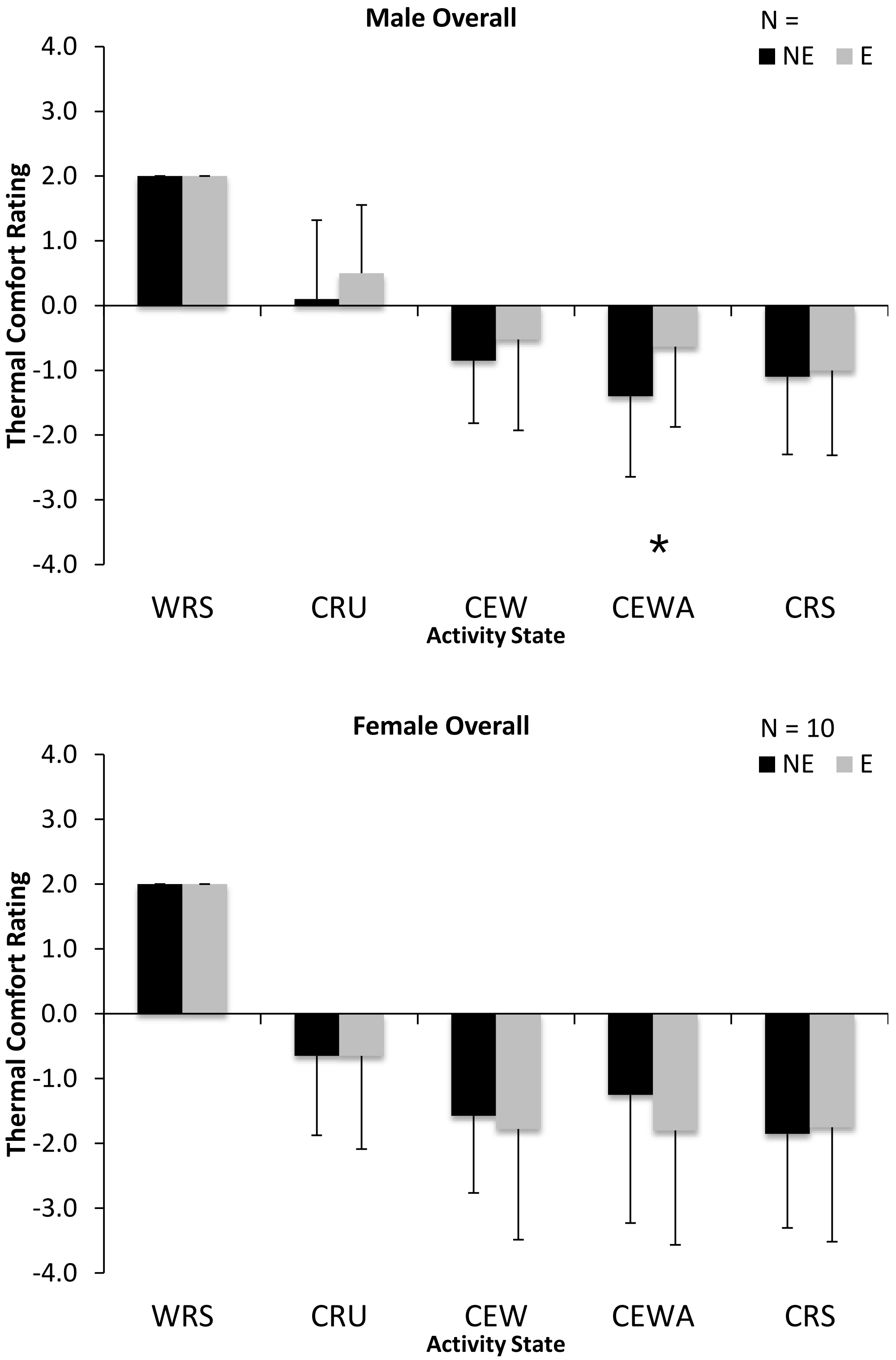


Figure 2.23 Overall thermal comfort (TC_{OV}) comparing both NE and E coat for males and females; * $p<0.05$

Chapter 3.

Differences in Cutaneous Temperature Sensitivity between Males and Females

3.1. Introduction

While it is widely believed that human body composition and adipose tissue insulation plays a large role in sex difference cognitive and physiological response to cold (55, 82, 85), it is argued that cutaneous temperature sensitivity neurons play an important role in determining temperature dependent behavioural responses (29, 30). Recently, transient receptor potential (TRP) channels have been linked with temperature detection and sensation (71). These TRP channels provide a putative link between cold sensitive neurons and thermal perception as well as physiological responses to the cold. Many different factors including body mass index (BMI) (27), race (27, 76), age (4, 17, 76), and skin temperature (23, 27) influence cutaneous temperature sensitivity. Even pressure of application of the thermode probe has been shown to be an influential factor in thermal threshold testing (36).

No agreement has been reached on the sex specific differences in cutaneous thermal thresholds (17, 27, 30, 34, 48, 52, 53). While Golja et al.

have shown that females have lower thermal thresholds compared to males, there is a lack of a clear physiological mechanism to explain these differences (17, 30, 53). It was suggested that thermosensitivity differences among sexes could be related women having a greater temperature sensitive neuron density compared to men (11, 30). More concentrated cutaneous temperature sensitive neurons would lead to greater spatial summation of receptor signals leading to greater thermosensitivity in women compared to men. It has also been suggested that differences in thermosensitivity between sexes may be due to greater skin thickness among men compared to women which would influence time to respond to temperature stimuli in men compared to women, decreasing thermosensitivity in men (30). Few studies have controlled for fluctuations in core temperatures due to the menstrual cycle hormones in women. As sex is important factor in thermal threshold detection, it is necessary to identify differences in thermal threshold among sexes to properly understand the underlying physiological mechanism involved in thermosensitivity and the cold response. Furthermore, few studies have controlled for the effect of pressure during thermal cutaneous temperature sensitivity.

In this study after controlling for confounding influences of thermode application pressure, for cutaneous temperature sensitivity testing using the Method of Limits and Method Levels, it was hypothesized that females would be more sensitive to temperature changes on the skin compared to males. It was also hypothesized that females would be more sensitive to temperature changes on the skin on the dorsum of the hand, chest, and upper back compared to males when assessed using the Method of Levels and Method of Limits.

3.2. Methods

3.2.1. Ethics

Approval for this study was obtained from the Simon Fraser University Office of Research Ethics. The participant was provided the option of removing themselves from the study at any point at ant any time, without reason.

3.2.2. Participants

The participant was given an orientation in the laboratory of the equipment involved in this study and an explanation of the protocol. At the orientation, the participant could ask any questions they had about the study and they completed a Physical Activity Readiness Questionnaire (PAR-Q) and a health screen questionnaire. At the end of the orientation, the participant was given a 24 h reflection period. After the 24 h of reflection, an informed consent was given to the participant to be reviewed and signed. Upon arrival for their first testing session, each participant reviewed and signed the informed consent.

Each participant for the male and female groups was recruited to fit a medium size clothing ensemble. The measurements employed included a 40” chest, 30” waist, 40” hips, 34” arms and 31.5” inseam for males. For females: 36” chest, 28” waist, 39” hips, 31’ arms and 29” inseam. During the orientation session, each participant took time to ensure the clothing ensemble fit.

The recruited males had a mean age (± SD) of 25 (5) while females had a mean age of 30 (8). Males had an average height of 1.80 m (0.07) and an average weight of 77.4 kg (6.7). Females had an average height of 1.69 (0.04) and an average weight of 64.7 kg (5.4). Seven females were in follicular phase of the menstrual cycle, 2 females were in luteal phase and 1 female was had amenorrhea. A summary of the sample size justification can be seen in Table 2.1.

3.2.3. Instrumentation

Cutaneous Temperature Sensitivity

Pressure application of the thermode probe was assessed using two round Force Sensing Resistors® (FSR®, Interlink Electronics, Camarillo, CA, USA) with an area of 0.16 cm^2. A 15.82 cm^2 plexiglass rings and a plastic collar shaft (Zoro, Inc, Buffalo Grove, IL, USA) attached to a thermode probe (NTE-2A, Physitemp Instruments Inc., Clifton, NJ, USA). The force sensing resistors were mounted on opposite sides of one of the upper plexiglass rings. Both resistors were placed in between the rings such that when pressure was being applied to the tip of the probes the force sensors were activated to detect the forces. This set-up allowed for simultaneous thermal threshold and pressure sensitivity detection. Both the thermode probe and the force sensing resistors were connected to a National Instruments data acquisition system (SCXI-1000, Austin, TX, USA) controlled by a computer with LabVIEW software (Ver. 7.1, National Instruments, Austin, TX, USA).

The thermode probe employs a Peltier element which allows for control of the heat flux generated by applying current throughout the probe. Temperatures are simulated via a stream of cooled water from the pump and tank unit in the Physitemp (NTE-2A, Physitemp Instruments Inc., Clifton, NJ, USA). Data was collected by a data acquisition system controlled by LabVIEW software and stored on a laptop. Additionally, data was also recorded by hand on data sheets and kept in a binder.

Skin and Core Temperature and Surface Heat Flux

Skin temperature at each testing site sites using thermocouples (Thermonetics, California USA). The testing sites were measured at the upper back (T_{UB}), dorsum of the hand (T_H) and chest (T_{CH}). Skin thermocouples were attached at the testing sites using hypoallergenic tape (Transpore, 3M, St. Paul, MN, USA). Thermocouples used in skin temperature measurements was calibrated using a temperature controlled water bath (VWR Int, Model 1196, West Chester, Penn USA) in which the temperature was monitored by a platinum thermometer (Fisher Scientific, Nepean, ON, Canada

3.2.4. Data Acquisition

Skin temperature was sampled at a rate of 40 Hz and recorded every 1 s. The thermocouple was connected to a data acquisition system connected to a computer running LabVIEW software (Ver. 7.1, National Instruments, Austin, TX, USA).

Cutaneous temperature sensitivity temperatures was collected by the data acquisition system connected to a computer running LabVIEW software (Ver. 7.1, National Instruments, Austin, TX, USA). Pressure was maintained at 1.96 N and was monitored and collected by the data acquisition system connected to a computer running LabVIEW software (Ver. 7.1, National Instruments, Austin, TX, USA). Data was also recorded by hand using data sheets.

3.2.5. Protocol

Testing took place at room temperature at approximately 22°C and each testing session took about 30 min. Each male participant laid supine topless whereas females wore a sports bra. This duration was chosen to prevent limb cooling and to limit the time to prevent a decline in alertness. During thermal threshold testing, the thermode was applied at 1.96 N of force to maintain constant pressure. Two testing methods were employed: (1) Method of Limits and (2) Method of Levels. Testing occurred at three sites on the body, the dorsal surface of the hand, chest, and the upper back. The dorsum of the hand was chosen to represent the periphery and the chest and upper back were selected to represent the core region. The order of the two methods employed and the order of the tested sites were randomized. Two minute silent rest period between methods took place for the participant to familiarize with the pre-test temperature of 32°C.

While the volunteer was seated, the thermode was set to a resting pre-test temperature of 32°C, one of the two methods was employed. Using the (1) Method of Limits, the temperature of the thermode probe was decreased at a steady rate 1°C/s from 32°C. Once the volunteer detected any change in temperature, he or she gave an audible “yes” response. The time and temperature at which the positive “yes” response was given was recorded and the procedure was repeated for 6 trials. The average of the 6 trials was considered the thermal threshold value for the Method of Limits.

For the (2) Method of Levels, temperatures was initially decrease by 4°C from resting pre-test temperature of 32°C and then would quickly return back to 32°C. From each probe temperature the next decrement was halved from the previous decrement in temperature. For example the decrements were 4°C, 2°C, 1°C, 0.5°C, 0.2°C, 0.1°C, so we set temperatures at 32°C, 28°C, 26°C, 25°C, 24.5°C, 24.3°C, 24.2°C. When a response temperature level was detectable by the participant they provided an audible “yes” and the temperature increments increased by halving from previous temperature levels. When a “no” was given – signaling the participant can no longer detect changes, the decrements were doubled instead. The mean temperature between the last “yes’ and the “no” is taken and it is used as a thermal threshold value for data analysis.

3.2.6. Statistical Analysis

For cutaneous temperature sensitivity testing, cold threshold values were assessed using the mean of the six trials per measurement site from the Method of Limits and by taking the mean response value in the Method of Levels. Cold threshold values for both methods were determined for each of the three sites: Dorsum of the hand, chest, and upper back. Differences in cold threshold values were assessed between sexes using two-tailed unpaired t-tests with SPSS software (Version 23, Surrey, UK). Results were considered statistically significant if $p<0.05$.

3.3. Results

There was no significant difference in CST on the dorsum of the hand and using the method of levels (Fig. 3.1; $p = 0.49$) or the method of limits (Fig. 3.4; $p = 0.17$).

There was a trend on the chest (Fig. 3.2) using the method of levels ($p = 0.092$) for greater CST for males than females and male had significantly greater ($p = 0.047$) CST than females on the chest using the method of limits (Fig. 3.5). The method of levels on the chest (Fig. 3.2) showed that males could discriminate at 2.0°C (1.5°C) while females required larger temperatures to discriminate at 3.8°C (3.2°C). With the method of limits on the chest (Fig. 3.5), males could discriminate temperatures on average at 4.0°C (1.3°C), while females discriminated at a higher temperature of 5.9°C (2.7°C).

On the upper back, there was no significant difference in CST using the method of levels (Fig. 3.3; p = 0.19) or the method limits (Fig 3.6; p = 0.94)

3.4. Discussion

Results from CST using both Method of Limits and Method of Levels indicated that females are less sensitive to temperature changes on the chest compared to males. On the dorsum of the hand and at the upper back location there was no difference detected in temperature differentiation. While no difference was detected, females did on average have smaller thermal thresholds compared to males at the dorsum of the hand using the Method of Limits, as well females had a lower thermal threshold using the Method of Levels at the upper back. From our results we showed that chest thermosensitivity in women was less sensitive compared to males which may be explained due to underlying anatomical and physiological differences between the sexes.

Golja et al. have shown that when assessing peripheral thermosensitivity, females tend to be more sensitive to temperature changes when compared to males (30). Our results indicate male and female thermosensitivity was the same on the dorsum of the hand and the upper back. Few studies in the literature have looked at thermosensitivity at the chest or core region of the body (61). Our results give a novel indication that at the region of the chest females are less thermosensitive to males. The upper back was selected as a testing location as it was believed that there is a large amount of brown adipose tissue that may play a role in thermosensitivity (66). Our results indicate that there is not enough difference in temperature sensitivity in this region between sexes to detect a difference. Importantly, this study also shows these novel results while controlling for the application pressure of the thermode probe – removing it as a confounding factor commonly seen in CST.

It is widely accepted that cutaneous temperature sensitivity is due to detection by cutaneous temperature neurons (20, 71, 88). Golja et al have suggested that sex differences in cutaneous temperature sensitivity may arise from differences in concentration of temperature sensitive neuron (29, 30). Our results seem to be in agreement with this mechanism. It could be that there is less concentration of temperature sensitive neurons in females compared to males at the chest region of the body (11). Another suggested mechanism linked cutaneous temperature sensitivity with thickness of the skin (29, 30). As women have thinner skin in the periphery, they would have decrease time to respond to a temperature stimulus which is suggestive of a lower thermosensitivity (30). This was not seen in our results at the chest as women had a much more delayed response to the cold compared to males. In the cold females rely on a more pronounced vasoconstriction compared to males in order to maintain thermal balance (8, 55). This supports the results that females have greater thermosensitivity at the periphery, however, because the chest region does not need to undergo vasoconstriction as aggressively in the cold compared to the periphery, there less reliance on a need to detect cold in the chest region. It could be due to a greater concentration of temperature sensitive neurons elsewhere in the body that females are less thermosensitive compared to males at the chest.

It has been shown many factors can influence CST (4, 17, 20, 27, 29, 30, 50, 71, 77, 89). In our study, we used a novel pressure sensing thermode to standardize pressure to minimize any confounding results that may be due to variability of pressure of application. While we standardized as many parameters as possible, there are always other factors that could play a role in influencing thermosensitivity. As was mentioned earlier, skin thickness may play a role in thermosensitivity (30). Future studies looking at sex differences could look for standardization of skin thickness using ultrasound screening for temperature sensitivity testing through skin fold measurement before CST. This could assist in reducing variability seen in our results and may reveal novel mechanism on sex differences in thermosensitivity.

Conclusion

The hypothesis was that females would be more sensitive to temperature changes on the skin on the dorsum of the hand, chest, and upper back compared to males when assessed using the method of levels and method of limits. The data did not support the hypothesis for measurements on the dorsum of the hand and upper back. Contrary to the hypothesis it was shown that females are significantly less sensitive to temperature changes on the chest compared to the males.

3.5. Tables

Table 3.1 **Means and standard deviation of thermode pressure, skin temperature (T_{SK}) and dry bulb temperature (T_{DB}) for both methods and on all 3 sites.**

		Method of Levels			Method of Limits		
		Dorsum of the Hand	**Upper Back**	**Chest**	**Dorsum of the Hand**	**Upper Back**	**Chest**
Thermode Pressure	Male	1.95N (0.07)	1.98N (0.10)	1.93N (0.08)	1.91N (0.05)	1.95N (0.08)	1.87N (0.11)
	Female	1.95N (0.08)	1.90N (0.04)	1.90N (0.06)	1.91N (0.05)	1.93N (0.10)	1.91N (0.03)
T_{SK}	Male	31.7°C (1.1)	33.3°C (1.1)	32.9°C (0.5)	31.0°C (1.1)	32.6°C (1.2)	32.3°C (0.4)
	Female	31.2°C (3.1)	32.6°C (3.6)	32.4°C (3.5)	31.0°C (2.1)	32.6°C (2.9)	32.4°C (2.8)
T_{DB}	Male	25.0°C (0.7)	24.9°C (0.8)	25.1°C (0.7)	25.0°C (0.9)	24.9°C (0.9)	25.0°C (0.8)
	Female	25.0°C (0.7)	24.7°C (0.6)	24.8°C (0.7)	24.8°C (0.7)	24.7°C (0.7)	24.8°C (0.8)

3.6. Figures

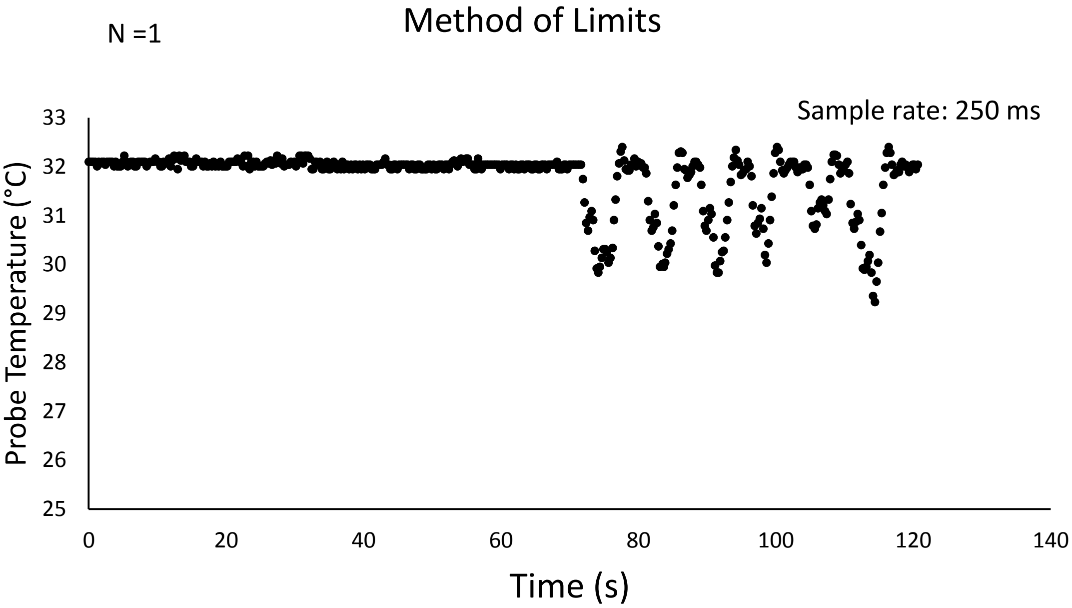


Figure 3.1 Sample of data for one volunteer using the Method of Limits

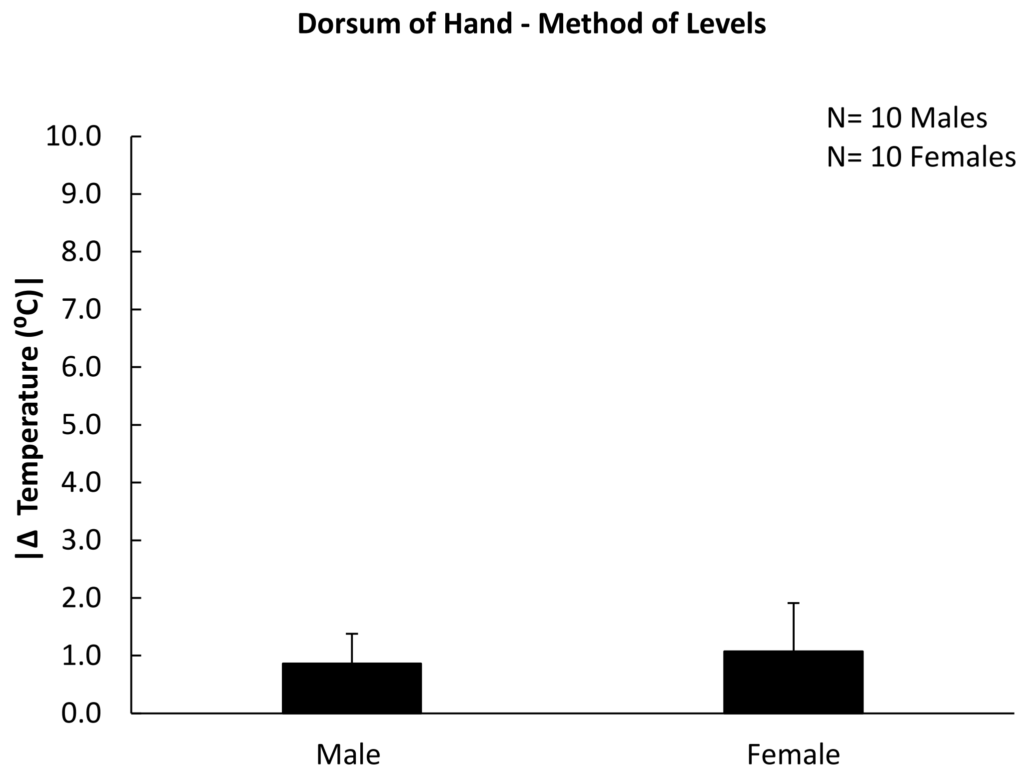


Figure 3.2 Absolute values of temperature change at the dorsum of the hand using the Methods of Levels.

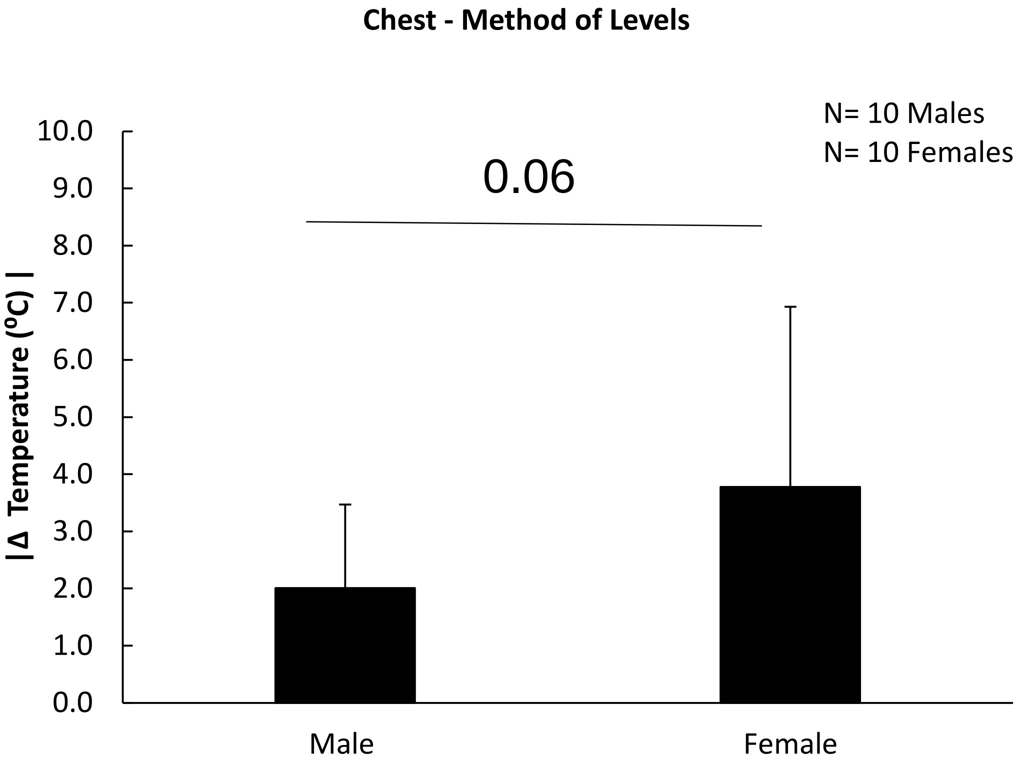


Figure 3.3 Absolute values of temperature change at the chest using the Methods of Levels..

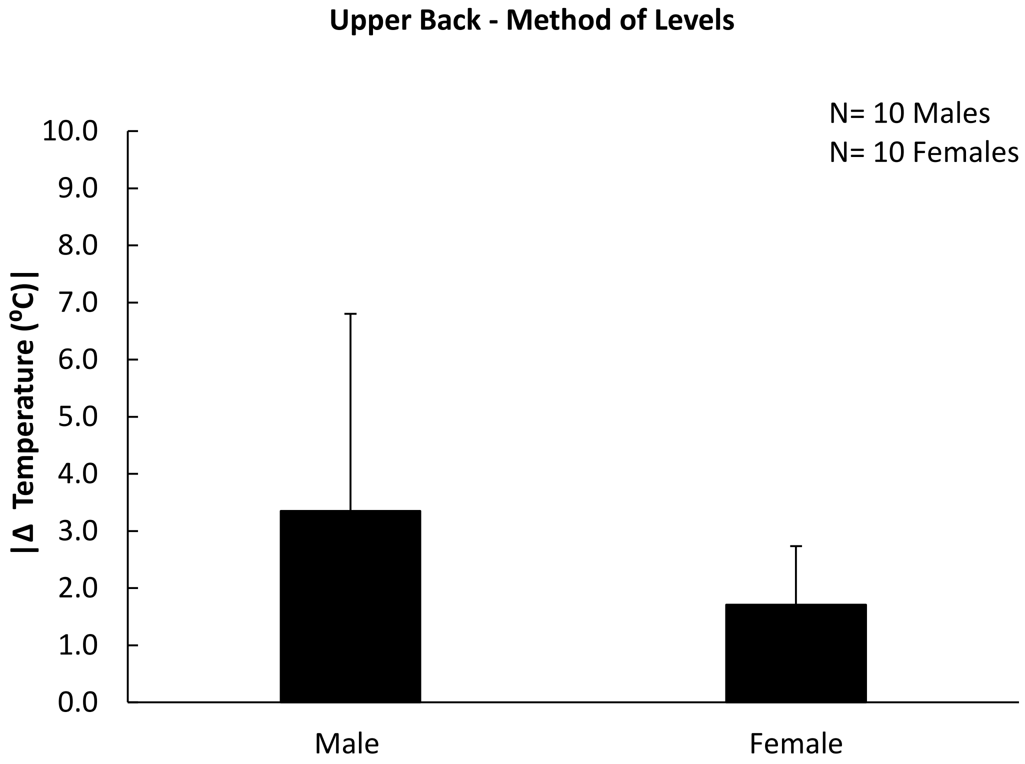


Figure 3.4 Absolute values of temperature change at the upper back using the Methods of Levels.

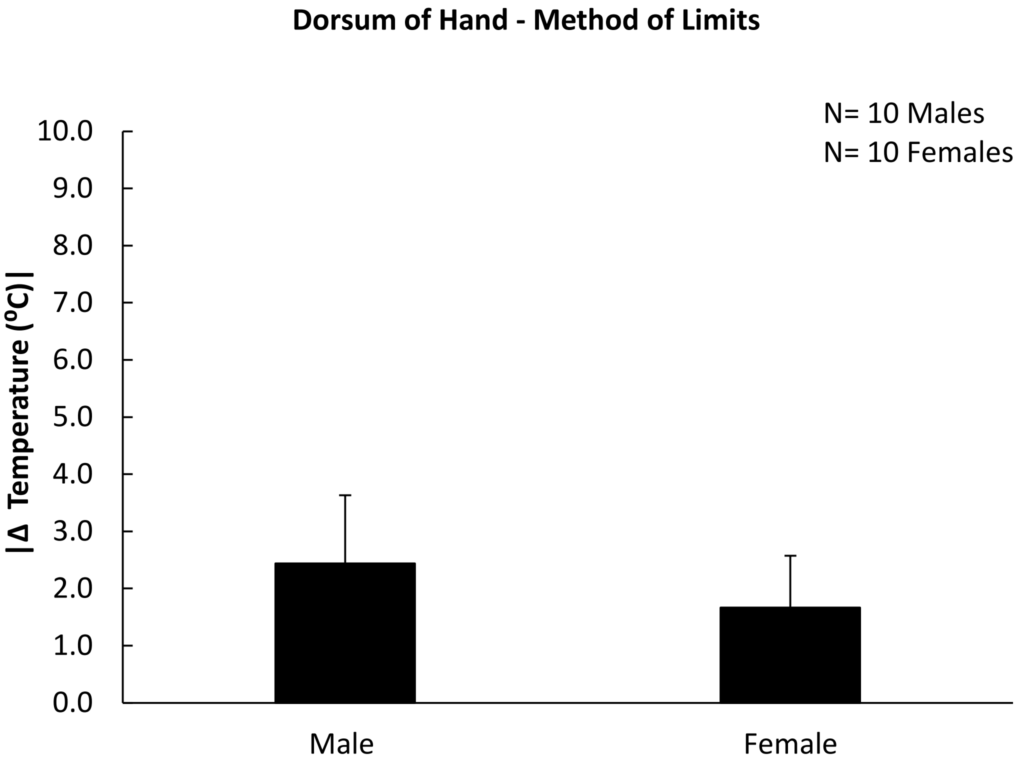


Figure 3.5 Absolute values of temperature change at the dorsum of the hand using the Methods of Limits.

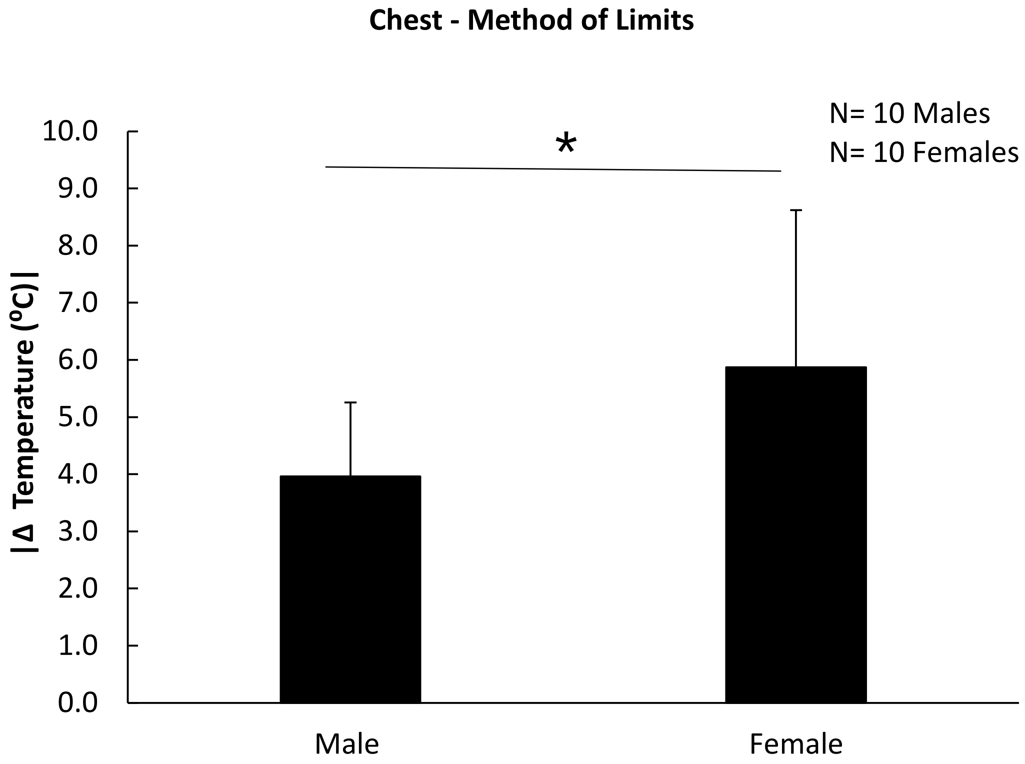


Figure 3.6 Absolute values of temperature change at the chest using the Methods of Limits; * $p<0.05$

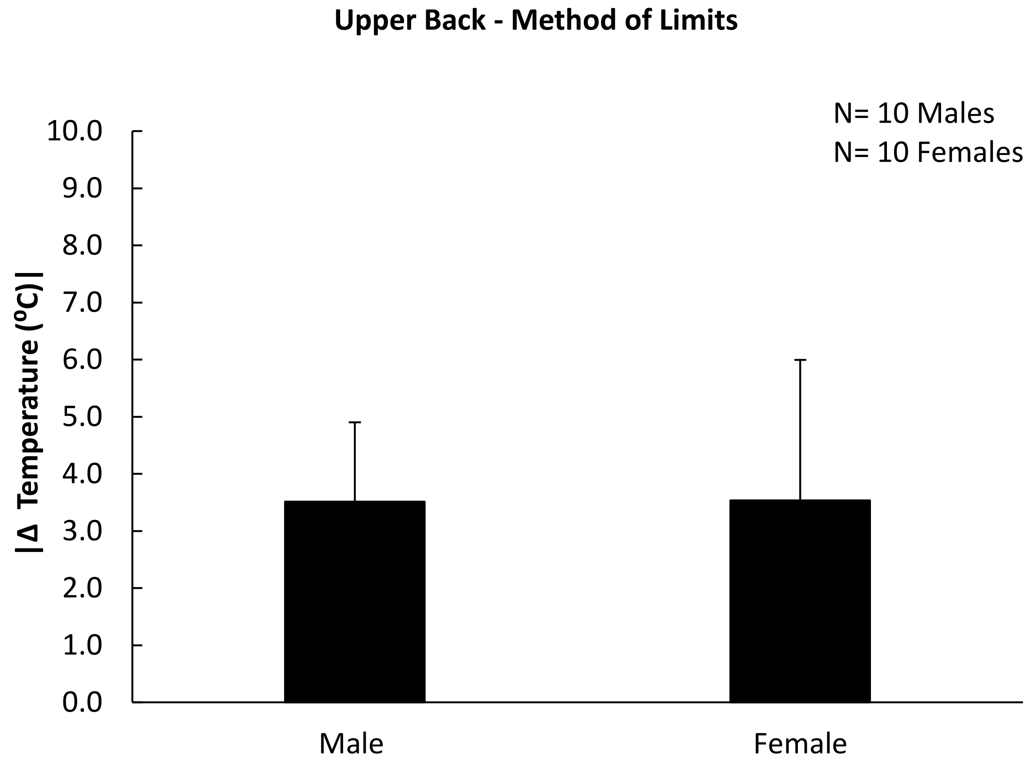


Figure 3.7 Absolute values of temperature change at the upper back using the Methods of Limits..

References

1. **Anttonen H, Niskanen J, Meinander H, Bartels V, Kuklane K, Reinertsen RE, Varieras S, and Sołtyński K**. Thermal manikin measurements--exact or not? *Int J Occup Saf Ergon* 10: 291-300, 2004.

2. **Arens EA, and Zhang H**. The skin's role in human thermoregulation and comfort. *In Thermal and moisture transport in fibrous materials (Pan N, Gibson P, eds), pp 560-602. Cambridge, UK: Woodhead Publising Ltd, 2006.*

3. **Benzinger TH, Pratt AW, and Kitzinger C**. The thermostatic control of human metabolic heat production. *Proc Natl Acad Sci U S A* 47: 730-739, 1961.

4. **Bertelsmann FW, Heimans JJ, Weber EJ, van der Veen EA, and Schouten JA**. Thermal discrimination thresholds in normal subjects and in patients with diabetic neuropathy. *J Neurol Neurosurg Psychiatry* 48: 686-690, 1985.

5. **Beshir MY, and Ramsey JD**. Comparison between male and female subjective estimates of thermal effects and sensations. *Appl Ergon* 12: 29-33, 1981.

6. **Blondin DP, Maneshi A, Imbeault MA, and Haman F**. Effects of the menstrual cycle on muscle recruitment and oxidative fuel selection during cold exposure. *J Appl Physiol (1985)* 111: 1014-1020, 2011.

7. **Blondin DP, Tingelstad HC, Mantha OL, Gosselin C, and Haman F**. Maintaining thermogenesis in cold exposed humans: relying on multiple metabolic pathways. *Compr Physiol* 4: 1383-1402, 2014.

8. **Burse RL**. Sex differences in human thermoregulatory response to heat and cold stress. *Hum Factors* 21: 687-699, 1979.

9. **Charkoudian N**. Mechanisms and modifiers of reflex induced cutaneous vasodilation and vasoconstriction in humans. *J Appl Physiol (1985)* 109: 1221-1228, 2010.

10. **Charkoudian N, and Stachenfeld N**. Sex hormone effects on autonomic mechanisms of thermoregulation in humans. *Auton Neurosci* 2015.

11. **Chen CC, Essick GK, Kelly DG, Young MG, Nestor JM, and Masse B**. Gender-, side- and site-dependent variations in human perioral spatial resolution. *Arch Oral Biol* 40: 539-548, 1995.

12. **Christensen R, Clough D, Kurz A, Plattner O, Sessler DI, and Xiong J**. Thermoregulatory vasoconstriction does not impede core warming during cutaneous heating. *Ann N Y Acad Sci* 813: 827-834, 1997.

13. **Davis JK, and Bishop PA**. Impact of clothing on exercise in the heat. *Sports Med* 43: 695-706, 2013.

14. **de Neeling JN, Beks PJ, Bertelsmann FW, Heine RJ, and Bouter LM**. Sensory thresholds in older adults: reproducibility and reference values. *Muscle Nerve* 17: 454-461, 1994.

15. **De Sousa J, Cheatham C, and Wittbrodt M**. The effects of a moisture-wicking fabric shirt on the physiological and perceptual responses during acute exercise in the heat. *Appl Ergon* 45: 1447-1453, 2014.

16. **Dimicco JA, and Zaretsky DV**. The dorsomedial hypothalamus: a new player in thermoregulation. *Am J Physiol Regul Integr Comp Physiol* 292: R47-63, 2007.

17. **Doeland HJ, Nauta JJ, van Zandbergen JB, van der Eerden HA, van Diemen NG, Bertelsmann FW, and Heimans JJ**. The relationship of cold and warmth cutaneous sensation to age and gender. *Muscle Nerve* 12: 712-715, 1989.

18. **Durnin J, and Womersley J**. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br. J. Nutr.* 32: 77-97, 1974.

19. **Eyolfson DA, Tikuisis P, Xu X, Weseen G, and Giesbrecht GG**. Measurement and prediction of peak shivering intensity in humans. *Eur J Appl Physiol* 84: 100-106, 2001.

20. **Filingeri D, Fournet D, Hodder S, and Havenith G**. Why wet feels wet? A neurophysiological model of human cutaneous wetness sensitivity. *J Neurophysiol* 112: 1457-1469, 2014.

21. **Fillingim RB, Maixner W, Kincaid S, and Silva S**. Sex differences in temporal summation but not sensory-discriminative processing of thermal pain. *Pain* 75: 121-127, 1998.

22. **Flouris AD, and Schlader ZJ**. Human behavioral thermoregulation during exercise in the heat. *Scand Journal of Med Sci Sports 25:* 52-64, 2015.

23. **Fowler CJ, Carroll MB, Burns D, Howe N, and Robinson K**. A portable system for measuring cutaneous thresholds for warming and cooling. *J Neurol Neurosurg Psychiatry* 50: 1211-1215, 1987.

24. **Frank SM, Higgins MS, Fleisher LA, Sitzmann JV, Raff H, and Breslow MJ**. Adrenergic, respiratory, and cardiovascular effects of core cooling in humans. *Am J Physiol* 272: R557-562, 1997.

25. **Gagge AP, Burton AC, and Bazett HC**. A practical system of units for the description of the heat exchange of man with his environment. *Science* 94: 428-430, 1941.

26. **Gavin TP, Babington JP, Harms CA, Ardelt ME, Tanner DA, and Stager JM**. Clothing fabric does not affect thermoregulation during exercise in moderate heat. *Med Sci Sports Exerc* 33: 2124-2130, 2001.

27. **Gerr F, and Letz R**. Covariates of human peripheral nerve function: II. Vibrotactile and thermal thresholds. *Neurotoxicol Teratol* 16: 105-112, 1994.

28. **Gerrett N, Ouzzahra Y, Coleby S, Hobbs S, Redortier B, Voelcker T, and Havenith G**. Thermal sensitivity to warmth during rest and exercise: a sex comparison. *Eur J Appl Physiol* 114: 1451-1462, 2014.

29. **Golja P, Kacin A, Tipton MJ, Eiken O, and Mekjavic IB**. Hypoxia increases the cutaneous threshold for the sensation of cold. *Eur J Appl Physiol* 92: 62-68, 2004.

30. **Golja P, Tipton MJ, and Mekjavic IB**. Cutaneous thermal thresholds—the reproducibility of their measurements and the effect of gender. *J Therm Biol* 28: 341-346, 2003.

31. **Gonzales BR, Hagin V, Guillot R, Placet V, and Groslambert A**. Effects of Polyester Jerseys on Psycho–physiological Responses during Exercise in a Hot and Moist Environment. *J Strength Cond Res* 25: 3432-3438, 2011.

32. **Ha M, Tokura H, Yanai Y, Moriyama T, and Tsuchiya N**. Combined effects of fabric air permeability and moisture absorption on clothing microclimate and subjective sensation during intermittent exercise at 27 degrees C. *Ergonomics* 42: 964-979, 1999.

33. **Hardy JD, and Du Bois EF**. Differences between men and women in their response to heat and cold. *Proc Natl Acad Nsci USA* 26: 389-398, 1940.

34. **Harju EL**. Cold and warmth perception mapped for age, gender, and body area. *Somatosens Mot Res* 19: 61-75, 2002.

35. **Havenith G**. Laboratory assessment of cold weather clothing. In: *Textiles for cold weather apparel.* Williams J (Ed) Publishing in Textiles: Number 93 ed. Oxford Cambridge New Delhi: Woodhead Publishing Limited; 2009.

36. **Heiser F, and McNair W**. Stimulus-Pressure and Thermal Sensation. *Am J Pyschol* 46: 580-589, 1934.

37. **Holmér I**. Assessment of cold exposure. *Int J Circumpolar Health* 60: 413-421, 2001.

38. **Holmér I**. Cold but comfortable? Application of comfort criteria to cold environments. *Indoor Air* 14 Suppl 7: 27-31, 2004.

39. **Holmér I**. Evaluation of cold workplaces: an overview of standards for assessment of cold stress. *Ind Health* 47: 228-234, 2009.

40. **Holmér I**. Heat exchange and thermal insulation compared in woolen and nylon garments during wear trials. *Text Res J* 55: 511-518, 1985.

41. **Holmér I**. Protective clothing against cold--performance standards as method for preventive measures. *Arctic Med Res* 51 Suppl 7: 94-98, 1992.

42. **Holmér I**. Protective clothing and heat stress. *Ergonomics* 38: 166-182, 1995.

43. **Holmér I**. Recent trends in clothing physiology. *Scand J Work Environ Health* 15 Suppl 1: 58-65, 1989.

44. **Holmér I**. Thermal manikin history and applications. *Eur J Appl Physiol* 92: 614-618, 2004.

45. **Hu Y, Li Y, and Yeung K**. Moisture Management tester: A method to characterize fabric liquid moisture management prpoerties, Textiles Res. J. 75(1), 57-62, 2005.

46. **Johnson DG, Hayward JS, Jacobs TP, Collis ML, Eckerson JD, and Williams RH**. Plasma norepinephrine responses of man in cold water. *J Appl Physiol Respir Environ Exerc Physiol* 43: 216-220, 1977.

47. **Kambiz S, Duraku LS, Holstege JC, Hovius SE, Ruigrok TJ, and Walbeehm ET**. Thermo-sensitive TRP channels in peripheral nerve injury: a review of their role in cold intolerance. *J Plast Reconstr Aesthet Surg* 67: 591-599, 2014.

48. **Karjalainen S**. Thermal comfort and gender: a literature review. *Indoor Air* 22: 96-109, 2012.

49. **Kellogg DL**. In vivo mechanisms of cutaneous vasodilation and vasoconstriction in humans during thermoregulatory challenges. *J Appl Physiol (1985)* 100: 1709-1718, 2006.

50. **Kolka MA, and Stephenson LA**. Effect of luteal phase elevation in core temperature on forearm blood flow during exercise. *J Appl Physiol (1985)* 82: 1079-1083, 1997.

51. **Kwon A, Kato M, Kawamura H, Yanai Y, and Tokura H**. Physiological significance of hydrophilic and hydrophobic textile materials during intermittent exercise in humans under the influence of warm ambient temperature with and without wind. *Eur J Appl Phyiol* 78: 487-493, 1998.

52. **Lautenbacher S, and Strian F**. Sex differences in pain and thermal sensitivity: the role of body size. *Percept Psychophys* 50: 179-183, 1991.

53. **Liou JT, Lui PW, Lo YL, Liou L, Wang SS, Yuan HB, Chan KH, and Lee TY**. Normative data of quantitative thermal and vibratory thresholds in normal subjects in Taiwan: gender and age effect. *Zhonghua Yi Xue Za Zhi (Taipei)* 62: 431-437, 1999.

54. **Lopez M, Sessler DI, Walter K, Emerick T, and Ozaki M**. Rate and gender dependence of the sweating, vasoconstriction, and shivering thresholds in humans. *Anesthesiology* 80: 780-788, 1994.

55. **Marriott BM, and Carlson SJ**. *Nutritional Needs in Cold and High-Altitude Environments:: Applications for Military Personnel in Field Operations*. National Academies Press, 1996.

56. **Martineau L, and Jacobs I**. Muscle glycogen availability and temperature regulation in humans. *J Appl Physiol (1985)* 66: 72-78, 1989.

57. **Matsuda-Nakamura M, Yasuhara S, and Nagashima K**. Effect of menstrual cycle on thermal perception and autonomic thermoregulatory responses during mild cold exposure. *J Physiol Sci* 65: 339-347, 2015.

58. **McArdle W, Magel J, Spina R, Gergley T, and Toner M**. Thermal adjustment to cold-water exposure in exercising men and women. *J App Physiol* 56: 1572-1577, 1984.

59. **McArdle WD, Magel JR, Gergley TJ, Spina RJ, and Toner MM**. Thermal adjustment to cold-water exposure in resting men and women. *J Appl Physiol Respir Environ Exerc Physiol* 56: 1565-1571, 1984.

60. **Melikov A**. Breathing thermal manikins for indoor environment assessment: important characteristics and requirements. *Eur J Appl Physiol* 92: 710-713, 2004.

61. **Nadel E, Mitchell J, and Stolwijk J**. Differential thermal sensitivity in the human skin. *Pflügers Archiv* 340: 71-76, 1973.

62. **Neufer PD, Young AJ, Sawka MN, and Muza SR**. Influence of skeletal muscle glycogen on passive rewarming after hypothermia. *J Appl Physiol (1985)* 65: 805-810, 1988.

63. **Nielsen R, Olesen BW, and Fanger PO**. Effect of physical activity and air velocity on the thermal insulation of clothing. *Ergonomics* 28: 1617-1631, 1985.

64. **Nunneley SA**. Heat stress in protective clothing. Interactions among physical and physiological factors. *Scand J Work Environ Health* 15 Suppl 1: 52-57, 1989.

65. **Olesen B, Sliwinska E, Madsen T, and Fanger P**. Effect of body posture and activity on the thermal insulation of clothing: Measurements by a movable thermal manikin. *ASHRAE transactions* 88: 791-805, 1982.

66. **Osaka T, Kobayashi A, Namba Y, Ezaki O, Inoue S, Kimura S, and Lee TH**. Temperature-and capsaicin-sensitive nerve fibers in brown adipose tissue attenuate thermogenesis in the rat. *Pflügers Archiv* 437: 36-42, 1998.

67. **Park Y, Pendergast D, and Rennie D**. Decrease in body insulation with exercise in cool water. *Undersea Biomed Res* 11: 159-168, 1984.

68. **Parson KC**. Human Thermal Environment. 11 New Fatter Lane, London: Taylor & Francis Inc,, 2003.

69. **Pozos RS, and Iaizzo PA**. Shivering and pathological and physiological clonic oscillations of the human ankle. *J Appl Physiol (1985)* 71: 1929-1932, 1991.

70. **Pérgola PE, Johnson JM, Kellogg DL, and Kosiba WA**. Control of skin blood flow by whole body and local skin cooling in exercising humans. *Am J Physiol* 270: H208-215, 1996.

71. **Schepers RJ, and Ringkamp M**. Thermoreceptors and thermosensitive afferents. *Neurosci Biobehav Rev* 33: 205-212, 2009.

72. **Schlader ZJ**. The human thermoneutral and thermal comfort zones: Thermal comfort in your own skin blood flow. *Temperature* 2: 47-48, 2015.

73. **Schlader ZJ, Simmons SE, Stannard SR, and Mündel T**. The independent roles of temperature and thermal perception in the control of human thermoregulatory behavior. *Physiol Behav* 103: 217-224, 2011.

74. **Sisignano M, Bennett DL, Geisslinger G, and Scholich K**. TRP-channels as key integrators of lipid pathways in nociceptive neurons. *Prog Lipid Res* 53: 93-107, 2014.

75. **Solianik R, Skurvydas A, Vitkauskienė A, and Brazaitis M**. Gender-specific cold responses induce a similar body-cooling rate but different neuroendocrine and immune responses. *Cryobiology* 69: 26-33, 2014.

76. **Sosenko JM, Kato M, Soto R, and Ayyar DR**. Determinants of quantitative sensory testing in non-neuropathic individuals. *Electromyogr Clin Neurophysiol* 29: 459-463, 1989.

77. **Stevens JC, and Green BG**. Temperature-touch interaction: Weber's phenomenon revisited. *Sens Processes* 2: 206-209, 1978.

78. **Stocks JM, Taylor NA, Tipton MJ, and Greenleaf JE**. Human physiological responses to cold exposure. *Aviat Space Environ Med* 75: 444-457, 2004.

79. **Söderberg K, Sundström Poromaa I, Nyberg S, Bäckström T, and Nordh E**. Psychophysically determined thresholds for thermal perception and pain perception in healthy women across the menstrual cycle. *Clin J Pain* 22: 610-616, 2006.

80. **Takahashi-Nishimura M, Tanabe S, and Hasebe Y**. Effects of skin surface temperature distribution of thermal manikin on clothing thermal insulation. *Appl Human Sci* 16: 181-189, 1997.

81. **Tikuisis P**. Prediction of the thermoregulatory response for clothed immersion in cold water. *Eur J Appl Physiol Occup Physiol* 59: 334-341, 1989.

82. **Tikuisis P, Jacobs I, Moroz D, Vallerand AL, and Martineau L**. Comparison of thermoregulatory responses between men and women immersed in cold water. *J Appl Physiol (1985)* 89: 1403-1411, 2000.

83. **van Marken Lichtenbelt W**. Brown adipose tissue and the regulation of nonshivering thermogenesis. *Curr Opin Clin Nutr Metab Care* 15: 547-552, 2012.

84. **van Marken Lichtenbelt WD, and Schrauwen P**. Implications of nonshivering thermogenesis for energy balance regulation in humans. *Am J Physiol Regul Integr Comp Physiol* 301: R285-296, 2011.

85. **Wagner JA, and Horvath SM**. Influences of age and gender on human thermoregulatory responses to cold exposures. *J Appl Physiol (1985)* 58: 180-186, 1985.

86. **Wyndham C, Morrison J, Williams C, Bredell G, Peter J, Von Rahden M, Holdsworth L, Van Graan C, Van Rensburg A, and Munro A**. Physiological reactions to cold of Caucasian females. *J App Physiol* 19: 877-880, 1964.

87. **Yao Y, Lian Z, Liu W, and Shen Q**. Experimental study on physiological responses and thermal comfort under various ambient temperatures. *Physiol Behav* 93: 310-321, 2008.

88. **Yarnitsky D, Kunin M, Brik R, and Sprecher E**. Vibration reduces thermal pain in adjacent dermatomes. *Pain* 69: 75-77, 1997.

89. **Young AJ**. Effects of aging on human cold tolerance. *Exp Aging Res* 17: 205-213, 1991.

90. **Young AJ, and Castellani JW**. Exertion-induced fatigue and thermoregulation in the cold. *Comp Biochem Physiol A Mol Integr Physiol* 128: 769-776, 2001.

91. **Young AJ, Muza SR, Sawka MN, Gonzalez RR, and Pandolf KB**. Human thermoregulatory responses to cold air are altered by repeated cold water immersion. *J Appl Physiol (1985)* 60: 1542-1548, 1986.

92. **Young AJ, Sawka MN, Levine L, Burgoon PW, Latzka WA, Gonzalez RR, and Pandolf KB**. Metabolic and thermal adaptations from endurance training in hot or cold water. *J App Physiol* 78: 793-801, 1995.