Technical apparel performance for women during rest and exercise in a cold environment

by

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B.Kin., University of Manitoba, 2015

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

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SIMON FRASER UNIVERSITY
Spring 2018

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Abstract

At an ambient temperature of -4°C, in 3 trials, while wearing 1 of 3 differently designed jackets, 10 women ran for 15 min, rested for 10 min and ran again for 15 min. They were measured for body temperatures, heat flux and clothing microclimate conditions plus they gave thermal comfort votes. It was hypothesized for jackets that varied in the placement of their regional fabric thermal resistance either in an inverse proportion (Jacket 1) or in a direct proportion (Jacket 2) to previously reported T_{SK} (Fournet et al., 2013) that they would elicit different physiological responses and thermal comfort votes than a Control Jacket of consistent overall fabric thermal resistance, and, 2) that Jacket 1 would give better physiological responses and thermal comfort votes than Jacket 2. Results gave physiological responses that mostly followed as expected from the overlying fabric thermal resistance. Differing core temperature and regional physiological responses were evident between the 3 jackets but few results supported Jacket 1 had better physiological responses than Jacket 2. Jacket 1 gave significantly better thermal comfort votes than Jacket 2 and the Control Jacket in the first 15 min of exercise but the effects of the differing jacket designs were not evident in the second rest period and in the second 15 min exercise period. In conclusion, designing jackets with varied placement of regional fabric thermal resistance has potential to improve winter jacket performance.

Keywords: Clothing Physiology; Cold Stress; Exercise; Fabric Thermal Resistance; Core Temperature; Heat Flux; Microclimate; Regional Thermal Comfort; Skin Temperature; Technical Apparel

Dedication

I would like to dedicate this thesis to my friends and family. Your unwavering support and words of encouragement made this journey possible. I cannot thank you enough for all that you have done for me.

Acknowledgements

I would like to thank everyone who dedicated his or her time to my graduate studies. Thank you to my supervisor, Dr. Matthew White and my committee members Dr. George Havenith and Dr. Michael Walsh for their wisdom, expertise and guidance throughout this project. I would also like to thank the members of the project from lululemon athletica including Dr. Robert Gathercole, Dr. Andreas Jack, Bart Sciccitano, Sarah Manson, Kate Henderson, Erica Buckeridge, Jessie Croll, Katherine Le, Lisa Nguyen, Ellie Falzone, John Makowsky and Connor Hammond for their knowledge and support. Data collection and other various tasks for this thesis would not be possible without the help from my lab mates: Brandon Watson, Corrine Malcolm, Emily Lefler, Dora Hsiao, Peter Lee, Jaiden Choi, Matthew Dorton, Mike Rogers and Jingkai Pang. Thank you to the members of the department: King Chao, Joe Wang, Maggie Yeung, and Clare Zheng. Finally, thank you to all the volunteers who dedicated their time to make this project possible.

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List of Acronyms

ANOVA	Analysis of Variance
BMI	Body Mass Index
$\dot{C}$	Rate of Convective Heat Exchange
$\dot{E}$	Rate of Evaporative Heat Loss
HF	Surface Heat Flux
HR	Heart Rate
I	Body Tissue Insulation
$\dot{K}$	Rate of Conductive Heat Exchange
LH	Luteinizing Hormone
$\dot{M}$	Metabolic Rate
MC_{RH}	Microclimate Relative Humidity
MC_{TEMP}	Microclimate Temperature
NPY	Neuropeptide Y
$\dot{R}$	Rate of Heat Exchange by Radiation
R_{CT}	Conductive Thermal Resistance of Fabric
R_{ET}	Vapour Resistance of Fabric
$\dot{S}$	Rate of Heat Storage
T_{DB}	Dry Bulb Temperature
TC	Thermal Comfort
T_{SK}	Skin Temperature
T_{C}	Core Temperature
T_{PILL}	Core Temperature Pill
$\dot{V}O2$	Rate of Oxygen Consumption
$\dot{W}$	Rate of External Work Performed by the Body on the Environment or by the Environment on the Body

Glossary

Body Mapping	Regional physiological or perceptual responses across the body surface (Fournet, Ross, Voelcker, Redortier, & Havenith, 2013).
Elastane	An elastic polyurethane material (De Sousa, Cheatham, & Wittbrodt, 2014)
Microclimate	Environment created between the skin and clothing as well as between the layers of clothing (Ha, Tokura, Yoden, & Holmér, 1998)
Neuropeptide Y	Sympathetic neurotransmitter that initiates vasoconstriction (Kellogg, 2006)
Thermal Comfort	Thermal comfort can be described as a sensation created by many factors to influence an overall satisfaction or dissatisfaction of the surrounding environment (Havenith, 2003; Holmér, 2004a)

Executive Summary

This thesis discusses two studies on the effects of varying the regional placement of fabric thermal resistance for 2 novel winter jackets of similar overall fabric thermal resistance on physiological and thermal comfort responses of women while performing moderate intensity exercise at an ambient temperature of -4°C. For both studies women rested for 10 min at room temperature (Rest Stage I) and after entering the climatic chamber exercised for 20 min (Exercise Stage I), rested while standing for 10 min (Rest Stage II) and exercised again for 15 min (Exercise Stage II). The first chapter of the thesis includes a statement of the problem, a literature review on each of the topics of avenues of heat exchange during rest and exercise, physiological responses to cold exposure, the menstrual cycle and thermoregulation, clothing physiology, body mapping of skin temperature and clothing design, as well as thermal comfort. A rationale for the two studies along with the hypotheses being tested in this thesis completes Chapter 1.

The second chapter is novel study on the effect of 3 different jacket designs on physiological responses of the women. The 2 novel jackets had similar overall fabric thermal resistance with Jackets 1 and 2 having varied regional placement of their same total fabric thermal resistance with respect to a control jacket that had consistent fabric thermal resistance throughout. Specifically Jacket 1 had regional fabric thermal resistance placed in an inverse proportion (Fournet et al., 2013) and Jacket 2 had regional fabric thermal resistance placed in a direct proportion to previously reported skin temperatures (Fournet et al., 2013). Physiological responses of the women included each of core temperature, skin temperature, surface heat flux as well as microclimate temperature and microclimate relative humidity during rest and submaximal exercise. It was hypothesized that Jackets 1 and 2 with varied placement of their regional fabric thermal resistance would provide different physiological responses than the Control Jacket with consistent placement of its fabric thermal resistance. The physiological results showed no differences between Jackets 1 and 2 and the Control Jacket for mean 8-site skin temperature and mean 8-site heat flux, but did show a difference in core temperature responses, with Jacket 2 giving a slower and smaller increase than the Control Jacket. Overall 4-site microclimate temperature for Jacket 2 was significantly greater than in Jacket 1 and closer to a thermoneutral skin temperature of 28°C for the first 20 min of exercise in the climatic chamber. When examining upper body regional

physiological responses at different points across the 3 climatic chamber trials there were some significant differences between the 3 jackets for regional skin temperatures, regional heat fluxes and lower back microclimate temperatures. Significant differences between jacket types in skin temperature were evident for the shoulder, upper arm and upper back. For regional HF the thorax, lower arm, wrist and upper back displayed significant differences as did lower back microclimate temperature between the 3 jackets. The results support that varying the location of regional fabric thermal resistance in these jackets can influence physiological responses of women running at submaximal exercise intensity in the cold.

The third chapter examined the effects of varied placement and of the same total of fabric thermal resistance in these same 2 novel jacket designs on both overall Thermal Comfort (TC) votes and regional TC votes. It was hypothesized that Jackets 1 and 2 would give different TC votes than the Control Jacket and that Jacket 1 would give better TC votes than Jacket 2. Overall TC as well the regional TC sites showed significant differences between the 3 jacket types except on the thorax and abdomen. This supports that varied placement of fabric thermal resistance in these jackets can influence thermal comfort. Jacket 1 compared to both the Jacket 2 and the Control Jacket gave better TC votes closer to thermoeutral during Exercise Stage I in the climatic chamber, but the effects of the differing jacket designs were not evident in the Rest Stage II nor in Exercise Stage II in the climatic chamber

Chapter 1.

Statement of the Problem

Does the pattern of regional fabric thermal resistance in garments influence the physiological responses for exercise in the cold? Specifically, for a given total fabric thermal resistance of a jacket does changing the regional pattern of that fabric thermal resistance in a winter jacket improve a women's' physiological responses in the cold during submaximal exercise and during transitions from exercise to rest and from rest to exercise? Different garment designs, including those with different fibre types or placement of insulation on the arms versus the trunk, have been employed on only a few occasions to try help improve physiological responses during prolonged, steady state, submaximal exercise (Gavhed & Holmér, 1996; Holmér, 1988; Nielsen & Nielsen, 1984). Despite different garment designs providing better physiological responses during prolonged steady state submaximal exercise, it becomes more difficult to optimize physiological responses during transitions in exercise intensity (Gavhed & Holmér, 1996; Katavoutas, Flocas, & Matzarakis, 2015). This was demonstrated in transitions from high to low intensity exercise in the cold, where rapid drops in skin temperature (T_{SK}) and core temperature (T_C) were not reflected by a similar drop in thermal comfort (TC) (Gavhed & Holmér, 1996). It remains unresolved what type of jacket design will optimize physiological, microclimate (MC) and consequently TC responses during all types of transitions in exercise intensity in a cold environment.

Thermal comfort, which varies with exercise intensity (Gagge, Stolwijk, & Hardy, 1967; Gagge, Stolwijk, & Saltin, 1969), is associated to T_{SK} and also to $T_{C,}$ as well it is influenced by the type of clothing that is being worn (Fanger, Hojbjerre, & Thomsen, 1974). It is also has been shown that across the surface of the upper body there are regional variations in T_{SK} and heat flux (Gerrett, Ouzzahra, Redortier, Voelcker, & Havenith, 2015; Keijzer, Woerlee, Kluver, & Buist, 1972). A potential approach is to optimize garment design to give better surface heat flux to allow for optimal T_{SK}, and MC conditions to potentially elicit better TC ratings.

At rest and during exercise, clothing influences heat exchange between the body and the environment by creating a microclimate between the skin and the clothing (Ha, Tokura, Yanai, Moriyama, & Tsuchiya, 1999). Microclimate conditions are influenced by the external environment, clothing properties and exercise intensity (Mayor, Couto, Psikuta, & Rossi, 2015). Each of these influence heat transfer between the clothing and the surrounding environment. For women in cold environments, an exhaustive literature review did not uncover studies, which varied the placement of fabric thermal resistance within an outdoor winter jacket and assessed for the influence of these types of designs on microclimate conditions.

The focus and purpose of this thesis was to assess how 2 different novel winter jacket designs with similar total fabric thermal resistance but varied in placement of the regional fabric thermal resistance influence physiological, MC and TC responses for women in cold conditions during steady state submaximal exercise and during transitions to and from rest and submaximal exercise.

1.1. Literature Review

1.1.1. Avenues of Heat Exchange and Thermoregulation During Rest and Exercise

Humans can be exposed to extreme environmental conditions at rest and during exercise. Internal heat is released during exercise in proportion to the intensity of the exercise (Gavin, 2003). The body has a control system to regulate T_C that employs 3 main thermoregulatory responses: shivering, eccrine sweating and vasomotor responses. These responses influence various avenues of heat exchange from the body to the environment or vice versa. The rate of heat storage (Equation 1) is determined by the sum of the rates of heat exchange from avenues including metabolism, conduction, convection, radiation, and evaporation (Gavin, 2003; Havenith, 1999; Kenney, 1998):

$$\dot{S} = \dot{M} \pm \dot{W} - \dot{E} \pm \dot{K} \pm \dot{C} \pm \dot{R} \quad (\mathrm{W/m^2}) \quad \text{(Equation 1)}$$

Where $\dot{S}$ represents the rate of heat storage, $\dot{M}$ is the metabolic rate, $\dot{W}$ is the rate of external work by the body performed on the environment or from the environment performing work on the body, $\dot{E}$ is the rate of evaporative heat loss, $\dot{K}$ is the rate of conductive heat exchange, $\dot{C}$ is the rate of convective heat exchange, and $\dot{R}$ is the rate of heat exchange by radiation.

Metabolic heat liberation from the body occurs at rest and its rate is increased during muscular work or shivering (Rintamäki & Rissanen, 2006). Exercise causes an increase in the metabolic rate where ~25% of the released energy is captured in high energy phosphate chemical bonds and ~75% of the energy released is converted to heat (Rintamäki & Rissanen, 2006). The goal of the thermoregulatory control system is to balance the rate of heat release from macronutrients and these rates of heat loss or heat gain (Equation 1) to allow a regulation of T_C. When environmental air has a temperature and a vapour pressure lower than the skin surface temperature and skin surface vapour pressure, heat loss through evaporation of sweat from the skin, evaporation of fluids from respiration, as well as heat loss by conduction, convection and radiation, oppose the body's metabolic increase in heat liberation (Gavin, 2003).

In addition to the rate of storage ($\dot{S}$) depending on the environmental conditions, other influences on $\dot{S}$ include if the individual is at rest or exercising and the amount of body surface area in contact with the ground. During rest in a thermoneutral environment, it is estimated evaporation aids in 25% of the body's heat loss and the remaining 75% is comprised of convection, conduction and radiation (Arens, 2006b). These proportions typically become reversed as the body engages in exercise, with the main source of heat loss occurring through evaporative heat loss (Arens, 2006b). According to Fanger (1973), eccrine sweat secretion increases by 42% of the change in metabolic heat transfer from rest to exercise (Fanger, 1973), however, the control of heat loss from eccrine sweating depends on surface T_{SK} and T_C as well as ambient RH and T_{DB} (Nadel, 1985).

Exposure to environments with a lower T_{DB} than T_{SK} will result in heat flow from the body to the surrounding air via the heat loss avenue of convection (Marriott, 1996). This convective response is greater in the presence of wind and with limb motion during dynamic exercise (Arens, 2006b; Havenith, 2003). In a still air environment a thick layer of heated air exists over the surface of the body, between 14-21 mm, depending on the tightness of the garment (Havenith, 1999), and this layer is diminished in the presence of wind (Arens, 2006b). Furthermore, the movement of air created by the limbs during exercise increases heat loss due to the difference in velocity of the limbs compared to the torso (Arens, 2006b), and this contributes to greater heat dissipation from the limbs during exercise (Nielsen, 1985).

When assessing winter jacket designs, heat lost or gained by the body can be estimated at various locations on the upper body surface with small heat flux disks (Yamane, Oida, Ohnishi, Matsumoto, & Kitagawa, 2010). An assessment of surface heat flux during exercise is essential to determining the jacket design that is best suited for women during rest and exercise in the cold in order to maintain an appropriate T_{SK} so as to elicit the best TC.

1.1.2. Physiological Responses to Cold

Primary autonomic thermoregulatory responses to cold exposure include cutaneous vasoconstriction and shivering thermogenesis (Stocks, Taylor, Tipton, & Greenleaf, 2004). A reduction in T_{SK} contributes to cold-induced vasoconstriction thereby shunting of warmer blood from the periphery to the core in order to help reduce convective/conductive heat loss (Bittel, Nonotte-Varly, Livecchi-Gonnot, Savourey, & Hanniquet, 1988; Rowell, Brengelmann, Blackmon, Twiss, & Kusumi, 1968; Stocks et al., 2004). Innervation of cutaneous circulation is by noradrenergic nerves that are responsible for vasoconstriction (Charkoudian, 2010). The mechanisms that control vasoconstriction includes the release of norepinephrine and a co-transmitter acting on α_1 and α_2 receptors as well as an inhibition of the nitric oxide system responsible for vasodilation (Hodges, Zhao, Kosiba, & Johnson, 2006). Stephens et al. (Stephens, Saad, Bennett, Kosiba, & Johnson, 2004) suggest a potential co-transmitter involved in cutaneous vasoconstriction to be Neuropeptide Y (NPY) and acts on NPY Y1 receptors. Neuropeptide Y is released by sympathetic fibres (Kellogg, 2006) and when NPY Y1 receptors are inhibited by the BIBP-3266 antagonist, there is an inhibition of vasoconstriction, further supporting NPY as a co-transmitter responsible for vasoconstriction (Stephens et al., 2004).

While cutaneous vasoconstriction response to the cold reduces the blood flow to the extremities and shunts it towards the core, shivering increases the rate of heat release from macronutrients to help maintain core temperature. The T_C threshold for the onset of shivering has been shown to differ between men and women. Lopez et al. (Lopez, Sessler, Walter, Emerick, & Ozaki, 1994) demonstrated the threshold for shivering in women occurred at a T_C 0.3°C higher than men. This demonstrates the importance of focusing on potential physiological differences between men and women's responses to cold. Not only are shivering T_C thresholds but also body composition is different between sexes (Solianik, Skurvydas, Vitkauskienė, & Brazaitis, 2014), which can have an influence on physiological responses to the cold. These differences in responses between the sexes in cold environments become important when designing winter apparel and support designs unique to either women or men.

At an ambient temperature of 10˚C, Wagner & Horvath (Wagner & Horvath, 1985) showed women relative to men maintained a consistently higher T_C, had lower T_{SK} and an earlier onset of their metabolic response to these conditions. The reduction in T_{SK} while maintaining a warmer T_C in cool environments, based on body fat percentage, is described as an ‘insulative’ response (Solianik et al., 2014). Body tissue insulation (I) is calculated by finding the difference between T_C and T_{SK}, multiplied by body surface area and 92% of the rate of metabolic heat ($\dot{M}$) transfer (Equation 2) (Y. S. Park, Pendergast, & Rennie, 1984; Solianik et al., 2014).

$$I\ (°C/(kcal \bullet m^{-2} \bullet h^{-1}) = (T_C - T_{SK})/0.92\ \dot{M} \pm \dot{S} \ldots\ldots\ldots\ldots \text{(Equation 2)}$$

Solianik et al., exposed men and women to acute cold stress of a cold water immersion at 14°C and observed that men had the greater metabolic responses than the women, whereas women had a greater insulative response (Equation 2) (Solianik et al., 2014).

The insulative response and body heat loss in women has been equated to body composition as well as to the surface area to mass ratio (Solianik et al., 2014; Wagner & Horvath, 1985). In both young men and women aged 8 to 20 the rate of cooling was shown to be negatively correlated to adiposity of the trunk and arms, whereas the surface area to mass ratio was positively correlated to rate of cooling (Sloan & Keatinge, 1973). In a review Burse summarizes how body morphology sex differences affects the ability to contribute or receive heat from the environment (Burse, 1979). In a study by McArdle et al. (1984), it was found that women have a larger surface area to mass ratio ($p<0.05$) as compared to men (McArdle, Magel, Spina, Gergley, & Toner, 1984). The surface area to mass ratio significantly influences the rate at which the body cools and this ratio has a larger effect on animals with a smaller body masses as suggested by Feist (1989) and as reviewed by Stocks (2004), hence supporting more rapid cooling is evident in women relative to men (Stocks et al., 2004). Geometrically, if you have the same surface area, but a smaller mass, on average, as women do compared to men, this gives a greater rate of heat loss (Burse, 1979). Accounting for these anthropometric differences that give different physiological responses can aid in the design of appropriate, women-specific outdoor apparel for cold exposure. Jacket design is important for women due to their smaller masses for the same or similar surface areas than men and this predisposes them to cooling.

1.1.3. Menstrual Cycle and Thermoregulation

Menstrual Cycle and Body Temperature

The menstrual cycle needs to be considered in the study of thermoregulation and garment design since there are menstrual cycle phase-dependent changes in T_C and mean T_{SK} (Kim & Tokura, 1995). Following the follicular phase, which is reported to have the lowest T_C in the menstrual cycle (Frascarolo, Schutz, & Jéquier, 1990; Israel & Schneller, 1950), the luteal phase is characterized by an increase in concentrations of, estradiol and progesterone, which appears to contribute to a higher T_C (Israel & Schneller, 1950). A high concentration of progesterone produces a thermogenic effect, causing an increase in T_C of 0.3-0.5˚C (Frascarolo et al., 1990), a greater heat loss and an increase in metabolic rate (Webb, 1986) all above resting values (Hessemer & Brück, 1985). These differences in body temperature between menstrual phases, needs to be taken into account when studying women in the cold and when designing, as well as testing women's winter apparel.

Menstrual Cycle and Physiological Responses to Cold

The thermoregulatory control of cutaneous vasoconstriction differs between the two phases of the menstrual cycle. The increase in T_C during the luteal phase relative to the follicular phase has been shown to elevate the T_C threshold triggering cutaneous vasoconstriction (Bartelink, Wollersheim, Theeuwes, van Duren, & Thien, 1990; Kenshalo, 1966).

This shift in thermoregulatory control of vasoconstriction during the luteal phase appears to match the higher resting T_C (Charkoudian & Johnson, 1999). Bartelink et al. compared the effect finger cooling in different the menstrual cycle phases had on peripheral finger T_{SK}, finger perfusion and forearm blood flow, concluding in the luteal phase finger T_{SK} was the lowest, the women had the largest vasoconstriction response and the slowest recovery as compared to the follicular phase (Bartelink et al., 1990). Kenshalo suggests that during the follicular phase, the temperature threshold at which a cool sensation is perceived is lower compared to the luteal phase, when skin temperature exceeded 36°C (Kenshalo, 1966). These findings further support the importance of testing women in the follicular phase to minimize the aforementioned hormonal influences on heat balance and thermal perception.

Menstrual Cycle and Clothing

The post-ovulatory luteal phase in the menstrual cycle appears to alter the metabolic rate (Webb, 1986) and, consequentially, this influences clothing choices (Kim & Tokura, 1995). Specifically, increased concentrations of progesterone during the luteal phase is thought to be a metabolic stimulant, causing a ~ 9% greater metabolic rate compared to the follicular phase (Webb, 1986). Kim and Tokura (Kim & Tokura, 1995) displayed the effect of the menstrual cycle phase on clothing preferences during a transition of ambient temperature from 30˚C to 15˚C. Specifically, during the luteal phase women dressed in thicker clothing sooner and at a higher T_C and T_{SK} as compared to the follicular phase (Kim & Tokura, 1995). The women reported a cooler mean temperature sensation in the luteal versus the follicular phase and their mean TC votes were closer to slightly uncomfortable during the 15˚C stage as compared to the 30˚C stage, (Kim & Tokura, 1995). This cooler sensation was explained by higher metabolic rates being coupled with an increase in skin thermal conductance (K_{SK}) during the luteal relative to the follicular phase (Kim & Tokura, 1995). Conversely, Frascarolo et al. observed the opposite findings to Kim et al. (Kim & Tokura, 1995), where K_{SK} was lower in the luteal phase compared to the follicular phase (Frascarolo et al., 1990). This discrepancy was attributed to differences in metabolic rates between the two experiments, which were 10-20 watts higher in Frascarolo et al's study (Frascarolo et al., 1990; Kim & Tokura, 1995), as well as differences in ambient temperatures where Frascarolo et al. only measured the volunteers in one ambient temperature of 28˚C. Considering these results, it is necessary to study women during the follicular phase with a tightly controlled ambient temperature and RH. Studying women in the follicular phase is to avoid menstrual-cycle-phase-associated significant increases in $T_{C,}$ $T_{SK,}$ cutaneous vasoconstriction thresholds and fluctuations in K_{SK} that stand to influence TC votes for a given garment.

Menstrual Cycle, Exercise Response and Oral Contraceptives

It has been shown that metabolic rate and heart rate (HR) are higher during the luteal phase (Kim & Tokura, 1995) as compared to the follicular phase, however responses to submaximal exercise under hot, dry heat stress, including $T_{C,}$ mean $T_{SK,}$ HR and sweat rate showed no difference between 4 women with regular menstrual cycles, 4 women with amenorrhea and 4 men (Frye, Kamon, & Webb, 1982). Therefore, women with normal menstrual cycles and women with amenorrhea seem to give comparable exercise induced physiological responses during heat stress, however it is also important to determine if oral contraceptives can affect physiological responses during exercise (Grucza, Pekkarinen, Titov, Kononoff, & Hänninen, 1993).

Grucza et al. (Grucza et al., 1993) conducted a comparison of women taking or not taking oral contraceptives during exercise for their thermoregulation on a cycle ergometer at room temperature of ~ 24°C, focusing on $T_{C,}$ T_{SK} and the onset of sweating responses. During exercise, mean T_C for those on oral contraceptives was greater in the luteal phase as compared to the follicular phase and a similar response was shown for those not on oral contraceptives. Their results suggest that any changes in $T_{C,}$ T_{SK} and onset of sweating is primarily influenced by menstrual phase and only negligibly by the presence of oral contraceptives (Grucza et al., 1993). Therefore, this supports, for studies of winter clothing, that women in the follicular phase, with or without oral contraceptive use, would have similar body temperature responses to exercise as compared to women with amenorrhea.

1.1.4. Clothing Physiology

Thermal Properties

In order to compensate for the physiological responses and heat loss evident with cold exposure, humans select garments that will keep them warm, allow appropriate movements and allow for heat balance while performing physical activities. Clothing is designed with an appropriate amount of fabric thermal resistance to prevent cold stress from impacting the body. Cold stress can cause unwanted heat loss, unwanted health risks such as hypothermia and cooling of extremities giving low T_{SK} that can give frostbite (Holmér, 1992). As an increase in workload occurs, the clothing must have the ability to compensate for both the increased rates of metabolic heat and water vapour release to prevent the individual from becoming over heated and causing sweat accumulation within the fabric (Havenith, 1999, 2003; Rintamäki & Rissanen, 2006). Following exercise, the sweat accumulated within the material begins to cool, causing the individual to feel cold; this is known as ‘after chill’ (Havenith, 2009). Therefore, an ideal garment for cold weather is one that can accommodate a fluctuation in a dynamic environment over a range of temperatures during different rates of movement or intensities of exercise (Havenith, 2009). Burton & Edholm (Burton & Edholm, 1955) first discussed how arctic mammals adjust their insulation by changing the thickness of their fur to protect themselves from cold temperatures. In relation to human responses to the cold, Burton & Edholm (Burton & Edholm, 1955), as cited by Holmér (Holmér, 1992), determined the appropriate clothing insulation required is dependent on the intensity of the activity being performed and on the climate in which the activity occurs. Holmér expanded on this concept that the amount of clothing insulation needed is related to both activity level and the environmental climatic conditions by creating a mathematical model, where $T_{SK,}$ sweating and heat storage remain at fixed values in order to isolate the appropriate conditions for physiological strain to maintain heat balance (Holmér, 1992). The level of clothing insulation, in Holmér’s model, increases linearly with decreases of environmental temperature (Holmér, 1992). The clothing insulation should also support the increase or decrease of activity levels in the cold by allowing appropriate ventilation and warmth during exercise as well as after a reduction of exercise intensity (Havenith, 2009). The clothing's ability to perform in these cold environments can be achieved by varying the heat resistance, vapour resistance, water tightness, air permeability and wicking properties of the clothing's fabric (Havenith, 2009).

During exercise, heat transfered by metabolism can be greater than heat loss from the body, causing body temperatures to be further elevated if the garment prevents or limits surface heat loss. The evaporative resistance of the garment is also an important factor in determining surface heat loss. A garment's influence on heat exchange (Holmér, 1989) will be dictated largely by its fabric thermal heat resistance (R_{CT}) value ($m^2{\bullet}K{\bullet}W^{-1}$) and fabric evaporative vapour resistance (R_{ET}) value ($m^2{\bullet}Pa{\bullet}W^{-1}$). The heat and vapour resistance of clothing fabrics can be measured using a guarded hot plate. A guarded hot plate creates a temperature gradient between it's surface and the surrounding environment in order to quantify the amount of heat lost through a fabric (Havenith, 2009). Since these tests are static, the values acquired do not provide a full representation of the given fabric's thermoregulatory properties, due to the absence of wind, movements from exercise and moisture influences on microclimate that are evident for garments worn in cold environments (Holmér, 1989). This is important since exercise and wind have been reported to increase the air permeability of a garment (Bouskill, Havenith, Kuklane, Parsons, & Withey, 2002) and reduce by up to 26% the insulative properties of the basic insulation in the garment depending on the outer layer (Holmér, 1989). Therefore the garment insulation values are can be corrected in order to provide a more practical and accurate representation of their thermal insulation (Holmér, 1989) although this approach has not been adopted by all technical apparel designers. This is an important correction in order to properly assess the influence of varied insulation placement in a jacket on physiological responses for T_{SK}, HF, MC and TC votes while exercising in the cold where wind and body movement are present.

Fabrics and Thermal Resistance

A variety of fabrics with differing fabric thermal resistance values are available and have changed over time from animal based products, such as down feathers, to synthetic materials such as polyester. Fabric thermal resistance is dependent in part on the thickness of the fabric, in part on the type of fibre in a fabric as well as the construction of the garment. Together these fabric properties and garment designs influence the transfer of heat through a garment (Havenith, 2003). The fibres effect the quantity of radiative heat transfer between skin and the environment and conduction for dry heat transfer, but the thickness is a better determinant of clothing insulation values than the fibre type itself (Havenith, 2003). Clothing ensembles aim to provide warmth in cold climates, while allowing heat transfer from the body to the environment to occur, keeping the individual cool while performing exercise. During exercise, air is ‘pumped’ throughout the garment fabrics by limb movement, therefore appropriate fabric thermal resistance is required for a winter jacket to provide warmth during rest and maintain evaporative heat loss during exercise to prevent accumulation of sweat (Holmér, 1989). For women exercising and resting in the cold, not only is it important to have appropriate placement of the fabric thermal resistance but also the correct fabric thickness to allow for the appropriate rate of heat loss so as to maintain their warmth and TC.

Air movement throughout the fabric has a cooling affect on the body, whereas trapped air next to the body, as it does for arctic animals (Burton & Edholm, 1955), will help keep this air warm. An inverse relation exists between air permeability and thermal insulation for clothing ventilation (Ha et al., 1999). Fabrics with low permeability values, therefore, give garments that require more ventilation, especially in a cold environment when build up of condensation can occur (Holmér, 1989). Sweat accumulation can occur while performing moderate intensity exercise in sub-zero temperatures (Gavhed & Holmér, 1996), so it is important to chose appropriate fabric thermal resistance and fabric permeability for winter jackets to allow for proper ventilation to prevent sweat build up, while maintaining warmth in these types of cold environments.

Fabric selection can include natural fibres, synthetic fibres or a combination of both. Moisture transport and absorption are important characteristics and should be considered in the fabric selection process of garments for use in the cold. Natural fibres including cotton and wool have high absorption properties, leading to sweat retention (Dai, Imamura, Liu, & Zhou, 2008). These fibres have been reported as more comfortable, but have reduced effectiveness in cooling abilities (Gavin, 2003). Wool and cotton were shown produce higher T_{SK} and T_C during exercise than nylon, due to high moisture absorption properties (Holmér, 1985, 1989). Polyester fibres have been shown to cause greater sweat production with less absorption compared to natural fibres (Kwon, Kato, Kawamura, Yanai, & Tokura, 1998) and are associated with lower T_C, because of their increased vapour permeability (Gavin, 2003). Consequently the influence of fibre type on T_{SK} and T_C should be taken into account when choosing both the fabric for a jacket and when deciding on the placement of fabrics with differing thermal resistances in a jacket over areas of varied surface $T_{SK.}$

Mixed views exist on the importance of fibre selection on human (Kwon et al., 1998) thermoregulation while exercising in the cold. Comparisons between wool, nylon, cotton and polypropylene garments have been conducted during exercise by men for three-layered and single layered garments in 8°C and -2°C, and no differences in thermoregulation were identified between the garments of these 4 materials (Holmér, 1985; Vokac, Kopke, & Keul, 1976). For males exercising during a wear trial for a multi-layered wool or synthetic cold weather clothing ensemble, showed higher T_{SK} for the wool ensemble as well as skin wetness of the lower back in contrast to the synthetic ensemble (Gavhed & Holmér, 1996). Polyester, or synthetic fibres, have the ability to facilitate evaporative heat loss and have reduced sweat retention, therefore are widely used in sports wear (Ha et al., 1999). Polyesters may be a better choice than wool in a garment used during exercise for these reasons, or perhaps wool would be better suited over known areas of lower T_{SK} (Gavhed & Holmér, 1996). Long-sleeve T-shirts comprised of 94% cotton/6% elastane or 93% polyester/7% elastane were tested for physiological responses during exercise in a warm climate (De Sousa et al., 2014). Both T-shirts had similar physical properties, but differed in water vapour and air permeability and as a result, sweat absorption was greater in the cotton garment and sweat evaporation was significantly greater in the polyester garment (De Sousa et al., 2014). These differences in water transfer properties and fibre types are of great importance in the influence of garments on thermoregulation during exercise in varied ambient temperatures. It follows that varying the fibre types throughout a garment, may improve physiological and thermal comfort responses. It is also important to note the majority of the studies on fabric types are performed on men (De Sousa et al., 2014; Gavhed & Holmér, 1996; Holmér, 1985); therefore a study designed around woman can help provide future direction on fabric selections for winter jackets to elicit appropriate thermoregulation in the cold.

Sensations created by different materials influence the body surface area in contact with the material as well as the amount of moisture accumulation on the skin surface (Havenith, 2003). Skin wetness can impact the sensation of clothing against the skin by increasing the friction between the surfaces, creating discomfort (Havenith, 2003). In neutral to warm environments, as skin wetness increased with T_{SK}, the coefficient of friction increased, and this gave a positive correlation between moisture and skin friction (Gwosdow, Stevens, Berglund, & Stolwijk, 1986). Not only did friction between the skin a fabrics increase, but also the feeling from smooth to rough texture became more apparent (Gwosdow et al., 1986). These results support clothing design for winter jackets to be worn while performing exercise, should account for accumulation of sweat and a fabric design that transports moisture away from the skin in order to prevent the feeling of discomfort, fabric roughness and increased friction. This can be achieved through appropriate fabric thermal resistance placement and fibre type selection when designing jacket for use in cold winter conditions.

Fibre type greatly influences heat transfer between the body and the environment (Gavin, 2003). It is also important to take into account the construction of various fibre types and the possible alterations associated with T_{SK} and surface heat loss (Nielsen & Endrusick, 1990). The knit structure of fibres can affect T_{SK} and convective heat loss during intermittent exercise in a cool environment (Nielsen & Endrusick, 1990). Various fibre constructions exist including 1-by-1 rib knit, fishnet, fleece, interlock and double-layer rib and of these constructions. Of these various fibre constructions the fishnet facilitates the greatest evaporative heat loss (Bakkevig & Nielsen, 1995). An understanding of fibre types and construction is imperative in the assessment of clothing during exercise in the cold and the influence on heat transfer. The fibre types utilized in jacket designs can influence $T_{SK,}$ surface heat loss and potential TC votes. Consequently choosing fibre constructions is an important consideration when designing winter jackets.

External factors such as wind or movements from exercise can also influence fabric thermal resistance performance in garments. As mentioned earlier, thickness of a material is a major determinant of fabric thermal resistance in a garment. The presence of wind pushing against a garment or human movement can reduce the thickness of the material, ultimately decreasing its insulative properties (Havenith, 2003; Lu et al., 2015). The additive combination of wind and body movement can reduce vapour resistance by 60% - 80% for a given garment and greatly decreases the length of time the clothing can be worn in the cold (Havenith, 2003). Understanding that fabric thermal resistant properties can change with wind and movement is necessary knowledge when designing winter jackets and interpreting the clothing performance during exercise in cold environments.

Thermal Manikins

The use of thermal manikins has grown in popularity over the years. Assuming the costs for buying and operating a manikin can be managed, this is due to the ability of easily employing manikins to assess thermal insulation of materials in tightly controlled environmental conditions. The first model of thermal manikins dates back to the early 1940's, when a one-segment copper manikin was designed for the US army (Holmér, 2004b). Since then, thermal manikin development has grown immensely and the manikins can perform multiple functions applicable to development of technical apparel.

Following the first manufactured manikin, more complex models were designed in order to collect more detailed information. Manikins have progressed from whole body measurements to 15 segments or regional locations to represent segments of the entire human body. The impact of human movement on clothing insulative values prompted the creation of a moveable manikin to simulate activities such as walking and cycling. As such, in 1989, the first moveable female manikin was developed (Holmér, 2004b). A moveable manikin more closely simulates human movement and provides a more accurate representation of human based trials for a given garment.

Thermal manikins have become an additional resource for studying clothing physiology and the properties of materials. Measurements that can now be collected using thermal manikins includes the insulation of clothing, air movement around the manikin body, heat transfer coefficients, sweating, whole body, segmental or regional temperatures and even breathing functions (Melikov, 2004). Heat exchange through conduction, radiation and convection can be measured in all directions from the whole body manikin or regional locations of interest (Holmér, 2004b). The introduction of the ability to cool the manikin body allowed measurements of heat gain, which assisted in a better understanding performance of protective clothing (Holmér, 2004b). Thermal manikins can be tested in a wide range of ambient temperatures, humidity, and wind speeds. Measures from these tests can be used to assess heat transfer properties of clothing ensembles, microclimate conditions and to predict the impact of the environment on humans wearing the same clothing ensembles (Holmér, 2004b).

The use of thermal manikins in place of human based trials, brings in to question the reliability and reproducibility of the measurements on thermal manikins within and between laboratories. Repeatability for thermal insulation measurements in clothing within a laboratory has been reported to be between 96-98% for thermal manikins (Anttonen et al., 2004; Holmér, 2004b). For thermal manikins the variability between laboratories for reproducibility ranges between 5-10% (Holmér, 2004b). Due to the large variety of manikins available, large alterations exist between the models from construction to capabilities, therefore, there is a need for a standardization of the makes and models of the thermal manikins (Holmér, 2004b) in order to reduce the differences in reproducibility between laboratories employing thermal manikins.

Thermal manikins for physical measurements have been compared to human based trials to help understand the relation between the two methods of data collection. Cold protective clothing ensembles were tested on thermal manikins from ambient temperatures ranging from 0 to -50°C (Meinander et al., 2004). Human volunteers wore the same garments across the same temperature range while performing low and high levels of activity. The results were comparable between the thermal manikins and humans for 0 and -10°C, but at -25°C the sweat rates during exercise required adjustments between the two groups (Meinander et al., 2004). Thermal manikins have been shown to be very effective in static thermoregulatory responses while wearing different clothing ensembles, but during exercise they may be less effective (Holmér, 2004b).

The field of clothing physiology includes not only understanding the properties of materials and human physiological responses in garments built with differing materials, but also an understanding of cognitive responses including how an individual feels in the garment. Ratings of these feelings include ‘thermal comfort’ assessments by humans in a given clothing ensemble. Thermal manikins do not possess the ability predict or give TC ratings, which is a significant limitation when employing thermal manikins for clothing physiology and thermal comfort research. Consequently, in clothing research and development, human studies have a distinct benefit of allowing collection of human TC votes during the testing of differently designed clothing ensemble.

Microclimate

Clothing can act as a barrier to heat transfer between the skin surface and the environment based on the properties of the clothing material and the ability for the garment to trap air (Havenith, 2003). The environment within the clothing is known as microclimate, which can be the air layer between the skin and the inner layer of the clothing or a layer of still air associated with each layer of material in a garment or clothing ensemble (Ha et al., 1999; Havenith, 2003). A layer of still air in the clothing has an additive value to the thermal insulation of the clothing ensemble. This thermal insulation is comprised of the air between the skin and the material, the subsequent layer of material as well as the still air layer that sits outside of the clothing (Havenith, 1999, 2003). A smaller layer of air is present in tight fitting clothing as compared to loose fitting, but the main factors affecting microclimate are garment movement and the movement of the still air layer (Havenith, 1999, 2003). Convection in the microclimate is reliant on clothing ventilation and air permeability, which is inversely related to the insulation value of the garment's material (Havenith, 2009). Wind disrupts the outer layer of air and potentially the air layer within the garment depending on the air permeability of the material. When body movement occurs and when there is an increase in wind speed this can cause a reduction in the insulation properties of the garment (Havenith, 2003). Consequently, when assessing clothing designs, measurements of temperature and relative humidity in microclimates can be employed and this needs to be in carefully controlled climatic conditions. Li 2005 has shown a non-linear, inverse relationship between microclimate relative humidity and thermal comfort with greater thermal comfort evident when RH at the skin surface is about 45-48% (Li, 2005).

Body and limb movement influencing the warm air layer around the body as discussed above, this movement also influences microclimate conditions during exercise due to the pumping of air within the garment and between the different layers of clothing. In cold environments this causes a decrease in microclimate temperature from the convective movement of air between the skin and the clothing (Ha et al., 1999; Havenith, 2003). Fabric selection, garment construction and clothing ventilation may all influence the microclimate of a jacket while exercising in the cold. This suggests a variation placement of fabric thermal resistance in a winter jacket, can influence microclimate temperature and humidity. In women's winter jackets, the still air layers associated with varied placement of fabric thermal resistance to provide the best physiological and comfort responses at rest and during exercise, remain to be assessed in a comprehensive manner.

1.1.5. Body Mapping of Skin Temperatures and Clothing Design

Assessment of thermoregulation in women has had a central focus on whole body responses (Bernstein, Hick, Inouye, Johnston, & Ryan, 1956; Burse, 1979; Charkoudian, 2010), with a smaller focus of research on regional thermoregulatory responses (Fournet et al., 2013; Nielsen & Nielsen, 1984). Increased study of women's regional thermoregulatory responses promises to make an important addition to the field of clothing design. Regional responses to exercise, such as $T_{SK,}$ sweat rates and thermal sensitivity in women can shed light on the appropriate placement and amount of insulation necessary for to give the best performance of cold weather jackets. Nielsen & Nielsen looked at the effect of limb insulation compared to core insulation on thermal sensation during light cycle ergometer exercise of ~36 W and rest in 10˚C (Nielsen &

Nielsen, 1984). Lower T_C was evident when the limbs were insulated and not the torso. Varied T_{SK} responses were also observed, but the overall mean T_{SK} did not seem to affect thermal sensation votes (Nielsen & Nielsen, 1984). Thermal sensation was suggested (Nielsen & Nielsen, 1984), to been determined by a combination of T_C and a weighted regional T_{SK} equation to give a mean body temperature (T_b). Thermal sensation votes showed a strong positive correlation with T_b and therefore highlights the importance of the influence of regional T_{SK} and T_C for jacket designs with varied placement of fabric thermal resistance have on thermal sensitivity while exercising in the cold.

Mapping of regional T_{SK} illustrates differences in T_{SK} across the body's surface. Using Forward Looking Infra Red (FLIR) Thermography, Fournet et al. mapped regional T_{SK} responses of 9 men and 9 women exercising at 70% $\dot{V}O_{2MAX}$ for 40 min (Fournet et al., 2013). The resultant composite thermal body maps from 9 men and 9 women showed T_{SK} varied in temperature ranges over the surface of the body, where the upper back had a higher T_{SK} and the abdomen a lower T_{SK} (Fournet et al., 2013). Consequently this thermal body map provides a basis for which regional variations in the fabric thermal resistance of garments can be chosen so as to give T_{SK} that potentially elicits the best thermoregulatory and TC responses in the cold for women.

Body mapping of sweating patterns have also been documented for men and women performing 30-min bouts of exercise at two different intensities with a target HR between 125-135 bpm as well as 150-160 bpm in an ambient temperature of 25.7°C (Smith & Havenith, 2011). Although the men showed greater local sweat rates as compared to women, both sexes had the highest regional sweat rate on the central upper back. The upper back also gave the greatest increase in sweat rate associated with higher intensity exercise (Smith & Havenith, 2011). Body mapping of regional sweat rates is applicable to clothing design to allow for appropriate choice of fabric thermal resistance and ventilation in the design of garments in the regions with greater sweat rates. Understanding which body regions have higher sweat rates can be applied to the analysis and interpretation of regional T_{SK}, HF and TC and how the sweat rates may impact these physiological and TC responses.

Differences in regional thermal sensitivity to hot and cold stimuli have been observed in women during exercise and rest (Gerrett et al., 2015). Women had an increased sensation to the cold stimulus as compared to the hot stimulus, but these sensations were reduced during exercise (Gerrett et al., 2015). Body mapping of significant regional sensitivity differences are evident during rest and exercise (Gerrett et al., 2015). The anterior torso is more sensitive to the cold stimulus than the posterior torso during rest, but this relationship was reversed during the exercise phase (Gerrett et al., 2015). During rest and exercise the upper arms were more sensitive to the cold stimulus than the lower arms (Gerrett et al., 2015). Body mapping of thermal sensitivity may explain potential regional differences in TC votes among women exercising in the cold and is an important consideration when designing winter jackets.

The literature supports the importance of regional body mapping for $T_{SK,}$ local sweat rates and thermal sensitivity in women when designing winter jackets. Varied placement and amounts of fabric thermal resistance in a winter jacket may improve T_{SK} values, HF microclimate temperatures (MC_{TEMP}) and humidity (MC_{RH}) during exercise, facilitating better evaporative heat loss in areas of greater sweat production and help maintain better TC in the cold.

1.1.6. Thermal Comfort

Thermal comfort was defined, by Houghton (1923), as a sensation that included the following categories: cold, cool, slightly cool, comfortable, slightly warm, warm and hot (Houghton, 1923). Thermal comfort can also be described as a sensation created by many factors to influence an overall satisfaction or dissatisfaction of the surrounding environment (Havenith, 2003; Holmér, 2004a). These factors affecting TC include body fat percentage (Burse, 1979), whole body T_{SK} (Gerrett et al., 2015), and psychological influences including experience, time of exposure and perceived control (Nikolopoulou & Steemers, 2003). Temperature sensitive neurons located in the skin are sensitive to external stimuli such as heat and noxious cold. The neurons transduce the given temperature stimulus into a signal that is sent to the cerebral cortex where thermal perception occurs (Sisignano, Bennett, Geisslinger, & Scholich, 2014). Interpretation of these sensations allows an individual to perceive surface temperatures and from this they can evaluate if they are in a comfortable or an uncomfortable state. Core temperature and T_{SK} have been suggested to be determinants of TC responses and any deviations from the comfort zone creates discomfort (Flouris & Schlader, 2015; Gagge et al., 1967; Nakamura et al., 2008; Yao, Lian, Liu, & Shen, 2008). Exercise elevates T_C, reducing TC due to the deviation from a thermoneutral zone of T_C but T_{SK} may influence TC more than T_C (Flouris & Schlader, 2015; Schlader, Stannard, & Mündel, 2010). During exercise at a T_C above 37°C, lowering of T_{SK} improved TC and this supports that T_{SK} is the primary determinant of TC (Flouris & Schlader, 2015; Schlader et al., 2010).

Exercise-induced increases in body temperatures can activate sweating, especially in the heat, but also in the cold, causing accumulation of non-evaporated sweat on the skins surface (Flouris & Schlader, 2015). Skin wetness is another factor influencing thermal comfort. Non-evaporated sweat accumulates on the skin, creating an uncomfortable wet feeling (Flouris & Schlader, 2015; G, 2009; Havenith, 2003). Therefore, fabric selection when designing winter jackets is an important consideration in order to avoid moisture accumulation on the skin, which can alter TC votes.

Many different visual scales exist with a range of thermal ratings from very hot to extremely cold (Karjalainen, 2012). These scales have been utilized to determine TC during rest and various levels of exercise, in a wide range of ambient temperatures for individuals wearing a variety of clothing ensembles. Fanger utilized a predicted mean votes (PMV) thermal comfort scale determined that a T_{SK} between ~31-34°C would give a thermal comfort vote of 0 or neutral (Fanger, 1973), but these results have been suggested to be limited to an ambient temperature range from 10-30°C (Holmér, 2004a). Holmér provides a graph of another thermal comfort scale, known as the required clothing insulation (IREQ) scale, as a function of T_{SK} for standing and walking adults and showed the thermoneutral votes correspond to a T_{SK} of ~ 28°C (Holmér, 2004a). Holmér's IREQ as a function of T_{SK} was determined in ambient temperatures of -6°C to -22°C (Holmér, 2004a). Therefore a T_{SK} of ~ 28°C should induce a thermoneutral TC vote during exercise and rest trials in similar temperature cold conditions when assessing jacket designs. A modified version of the (IREQ) method, which is a continuous 9-point scale (Fig. 2.3) (Holmér, 2004a), is a preferred scale to employ in the cold exposures when assessing winter jacket performance.

Regional Thermal Comfort

Majority of thermal comfort studies focus on whole-body comfort (Gagge et al., 1967; Holmér, 2004a; Schlader et al., 2010; Shimazaki, Yoshida, & Yamamoto, 2015), whereas fewer studies have analyzed regional thermal comfort (M. Nakamura et al., 2013; M. Nakamura et al., 2008). Arens et al. measured regional and whole body thermal comfort in a cool environment for 15 females and 12 males (E. Arens, Zhang, & Huizenga, 2006a). During sitting their regional TC votes varied greatly between the various locations on the body for the same cold environment. Although this study did not compare sex differences in TC ratings, these results support the importance of further investigating regional responses to TC in a cold environment. Arens et al. (E. A. Arens, Zhang, & Huizenga, 2005) and Zhang et al. (Zhang, Huizenga, Arens, & Wang, 2004), both looked at regional TC by applying a local warm and cool stimuli to the skin in three environments including a warm, neutral and cool environment. Arens et al. suggested that regional TC of the back and thorax had a greater influence on overall TC votes, compared to other voting sites on the upper and lower body (Arens et al., 2005). Nakamura later summarized that the regional responses between these two studies were difficult to compare due to the differences in the size of the temperature stimulation (Nakamura et al., 2013). Despite the differences in temperature stimulation, Zhang et al. also suggested the thermal sensation on the back had the largest influence on overall TC (Zhang et al., 2004). This suggests that uniform regional TC responses to different ambient temperatures and local temperature stimuli requires further investigation in order to better predict regional TC responses. This also supports assessing regional TC responses is an important inclusion when assessing novel designs of women's winter coats.

A cold stimulus on the skin during whole-body mild cold exposure, showed a greater discomfort of the abdomen and chest compared to the thigh or face for an assessment of regional TC (Nakamura et al., 2006), whereas a warm stimulus on the chest and abdomen during whole-body cooling elicited the best thermal comfort (Nakamura et al., 2008). Regional thermal comfort was further investigated by Nakamura et al. on the upper back, lower back, abdomen as well as the upper arm (Nakamura et al., 2013). During whole-body mild cold exposure, a local cool temperature stimulus was placed on the skin. Cooling of the upper back, lower back and abdomen all increased thermal discomfort, yet did not influence overall body TC (Nakamura et al., 2013). Local warming of the same regional locations reduced thermal discomfort during mild whole-body cold exposure, but no influence on overall TC was detected (Nakamura et al., 2013). These studies clearly indicated that regional TC could vary despite no observed changes in whole-body thermal comfort. Nakamura et al. conducted these studies at rest; therefore it is warranted to further investigation to assess if regional TC during exercise is also independent of overall TC. These results from studies of regional TC responses stand to help enhance the understanding of regional TC responses from which better jacket designs can be made with the appropriate placement of regional fabric thermal resistance so as to create a garment that gives a better TC.

Thermal Comfort Compared in Women and Men

Differences in TC between the sexes have been equated to the effect of anthropometry on T_{SK} and T_{C} (Wagner & Horvath, 1985). Different surface areas of the body have been found to differ in thermal sensitivity (Nielsen & Nielsen, 1984). For example, the back is more sensitive to a thermal stimulus than the chest or abdomen in men (Crawshaw, Nadel, Stolwijk, & Stamford, 1975). For both men and women the evidence suggests sensitivity to a cold stimulus is greatest on the head, then the torso and is then reduced for the extremities (Gerrett et al., 2015; Nadel, Mitchell, & Stolwijk, 1973) As mentioned earlier, women have reduced thermal sensitivity to a cold stimulus during exercise compared to rest (Gerrett et al., 2015), which could influence TC ratings. Women also report feeling more uncomfortable than men in cold conditions (Karjalainen, 2012) and potentially in warm conditions as well (Beshir & Ramsey, 1981). This could be due to increased sensitivity to changes in ambient temperature by women to any deviations from T_{SK} and T_{C}, which influences TC ratings (Fanger, 1973). A comparison between thermal sensitivity for men and women to a warm stimulus during rest and exercise has been studied (Gerrett et al., 2014), but a comparison between the female and male responses to a cold stimulus requires further investigation. Due to these sex differences in thermal comfort and sensitivity during rest and exercise, it is warranted to independently design winter jackets for men and women as a consequence of their differences in sensitivity to temperature.

Cutaneous temperature sensitivity thresholds were shown to differ between men and women (Golja, Tipton, & Mekjavic, 2003). Under similar environmental conditions and T_{SK}, women displayed significantly lower cutaneous thermal thresholds to a cold sensation by almost half, as compared to men (Golja et al., 2003). This supports the reasoning as to why women feel colder than men and this needs to be further investigated to better understand the relationship between TC, cutaneous thermal thresholds and clothing designs.

It has also been suggested that women's thermal sensation to a cold stimulus is reduced compared to resting values during exercise (Gerrett et al., 2015). Studies (Crawshaw et al., 1975; Gerrett et al., 2015) suggest that a modified jacket design, including various insulated areas of the limbs and torso, may provide an improved design to give better thermal sensation (Crawshaw et al., 1975) and TC for exercise and rest.

1.2. Rationale

Physiological responses to the cold have been shown to differ for woman as compared to men (Lopez et al., 1994; Wagner & Horvath, 1985). Some of these responses have been linked to sex-dependent anthropometric differences in body composition and variations in body tissue insulation. Wagner & Horvath showed women could maintain a warmer core temperature despite lower skin temperatures in a cool climate, while also exhibiting an earlier onset metabolic response (Wagner & Horvath, 1985). These sex differences in physiological responses may influence subjective TC votes.

In addition to its sex dependent differences, TC is also influenced by the intensity of exercise (Gagge et al., 1967; Gagge et al., 1969), skin temperature (T_{SK}), core temperature (T_C) and the clothing that is being worn (Fanger et al., 1974). Thermal comfort and physiological responses to the cold have also shown to be affected by the menstrual cycle. Changes in T_C, skin thermal conductance (K_{SK}) and thresholds to cold sensations are altered by the menstrual phase (Kenshalo, 1966; Kim & Tokura, 1995). Due to menstrual cycle related differences in T_C that may influence TC, women are best studied in the follicular phase to avoid significant increases in T_C and any changes in skin conductance that are evident in the luteal phase (Frascarolo et al., 1990).

Clothing properties influence heat exchange between the body and the environment. A garment’s influence on heat exchange is dictated largely by its fabric(s) thermal heat resistance (R_{CT}, m^2•K •W^{-1}) and evaporative vapour resistance (R_{ET}, m^2•Pa•W^{-1})(Holmér, 1989). During exercise, an increase in metabolic heat transfer occurs, therefore a jacket must be designed to prevent the individual from becoming over heated and to allow for minimal sweat accumulation (Havenith, 2003). Microclimate is influenced by the external environment, clothing properties and the intensity of exercise, all of which influence heat transfer across the clothing (Mayor et al., 2015). Therefore microclimate temperature (MC_{TEMP}) and relative humidity (MC_{RH}) can potentially influence physiological and TC responses for women exercising in the cold.

Thermal comfort can be described as a sensation created by many factors to influence an overall satisfaction or dissatisfaction of the surrounding environment (Havenith, 2003; Holmér, 2004a). The interpretation of TC by an individual determines the environment, posture or clothing choices a person would make in order to maintain normal body temperatures and feel comfortable. Holmér showed that during standing and walking for men and women in cold conditions from -6°C to -22°C that skin temperature of ~28°C gave an IREQ vote of 0 that corresponds to thermoneutrality (Holmér, 2004a). To have the best thermal comfort while wearing clothing while resting and exercising in the cold, a study assessed regional skin temperatures of women and men exercising in the cold (Fournet et al., 2013). This outcome provided a rationale for the design of novel winter jackets. Placement of increased thermal resistance fabric over areas thought to be zones of high heat flux with low skin temperatures (Fournet et al., 2013) is suggested to reduce heat flux and give a skin temperature closer to a 28°C that this will elicit thermoneutral TC votes closer to 0. Jackets with this type of design are suggested to give the best physiological and TC responses for women exercising and resting in the cold relative to a jacket with fabric that has consistent thermal resistance.

1.3. Hypotheses

1.3.1. Study 1: Effect of Jacket Type on Physiological Responses During Rest and Exercise in the Cold

It was hypothesized for the same cold condition of -4°C and the same moderate exercise intensity, that 2 jackets of similar total fabric thermal resistance that have their fabric regional conductive/convective thermal resistance values placed either in an inverse proportion (Jacket 1) or in a direct proportion (Jacket 2) to previously reported T_{SK} (Fournet et al., 2013), would elicit different physiological responses relative to a jacket of consistent overall fabric thermal resistance.

It was also hypothesized that Jacket 1, with it's regional fabric thermal resistance values placed in an inverse proportion to previously reported T_{SK} (Fournet et al., 2013), would give better physiological responses than a jacket with it's regional fabric thermal resistance values placed in a direct proportion (Jacket 2) to previously reported T_{SK} (Fournet et al., 2013).

1.3.2. Study 2: Effect of Jacket Type on Thermal Comfort Votes During Rest and Exercise in the Cold

It was hypothesized in the same cold conditions of -4°C and at the same moderate exercise intensity, that 2 jackets of similar total fabric thermal resistance that have their regional fabric thermal resistance values placed either in an inverse proportion (Jacket 1) or in a direct proportion (Jacket 2) to previously reported T_{SK}, (Fournet et al., 2013), would elicit different TC votes relative to a jacket of consistent overall thermal resistance.

It was also hypothesized that Jacket 1, with its fabric regional thermal resistance values placed in an inverse proportion to previously reported T_{SK} (Fournet et al., 2013), would give T_{SK} closer to 28°C and an improved overall and regional TC relative to a jacket (Jacket 2) with regional fabric thermal resistance values placed in a direct proportion to previously reported T_{SK} (Fournet et al., 2013).

Chapter 2.

Effect of Jacket Type on Physiological Responses During Rest and Exercise in the Cold

2.1. Introduction

Fournet et al. body mapped men's and women's T_{SK} while running in the cold, and demonstrated that women had significantly lower regional T_{SK} than men (Fournet et al., 2013). These differences were apparent on the anterior and posterior legs, the upper and lower back, but similar body maps of T_{SK} distribution were evident for both sexes (Fournet et al., 2013). As suggested by Fournet et al., these differences in T_{SK} appear to be explained by previous findings of regional cutaneous perfusion at rest, where perfusion was higher on the chest as compared to the abdomen by almost 70% (Fournet et al., 2013; Goldberg, Sepka, Perona, Pederson, & Klitzman, 1990; D. H. Park, Hwang, Jang, Han, & Ahn, 1997). The regions of lower T_{SK} reported in Fournet et al's FLIR images (Fournet et al., 2013), have also been seen in previous work by Clark et al. during exercise (Clark, Mullan, & Pugh, 1977), which supports the importance of designing a jacket to accommodate for these regional differences during rest and exercise.

Regional differences in T_{SK} may be explained by the presence and density of cutaneous perforators (Merla, Mattei, Di Donato, & Romani, 2010; Taylor & Palmer, 1987). Cutaneous perforators are vessels that branch off from main arteries as a direct or indirect blood supply to the skin (Taylor & Palmer, 1987). Larger and longer perforators are seen in the neck, torso and upper arm in fewer numbers, whereas as small perforators are located in the lower arm in greater density (Taylor & Palmer, 1987). Following exercise, Merla et al., discovered higher T_{SK} in tree shaped branches on the chest and upper arms, which was suggested to be caused by large cutaneous perforators in those regions (Merla et al., 2010). Lower T_{SK} on the abdomen may be due to differences in the type of perforator vessels as compared to the thorax. Regional T_{SK} variations across the upper body during rest and exercise are important in determining the placement and amount of thermal resistance in a winter jacket.

The purpose of this study was to assess how varied regional placement of fabric thermal resistance in a jacket influences women's $T_{SK,}$ surface HF as well as core temperatures (T_{PILL}) and microclimate (MC) conditions while exercising at a moderate intensity in the cold.

Hypothesis 2.1: It was hypothesized for the same cold condition of -4°C and the same moderate exercise intensity, that 2 jackets of similar total fabric thermal resistance that have their regional fabric thermal resistance values placed either in an inverse proportion (Jacket 1) or in a direct proportion (Jacket 2) to previously reported T_{SK}, (Fournet et al., 2013),, would elicit different physiological responses relative to a jacket of consistent overall fabric thermal resistance.

Hypothesis 2.2: It was also hypothesized that Jacket 1, with its regional fabric thermal resistance placed in an inverse proportion to previously reported T_{SK} (Fournet et al., 2013), would give better physiological responses than a jacket (Jacket 2) with it's fabric thermal resistance values placed in a direct proportion to previously reported T_{SK} (Fournet et al., 2013).

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 and time, without reason.

2.2.2. Participants

Each woman, prior to her first trial, completed a medical history form and a physical activity readiness questionnaire (PAR-Q) and signed an informed consent form. Each volunteer was also asked to provide information regarding the start date and the duration of their menstrual cycle in order to schedule each of their trials in the follicular phase of their menstrual cycle. The dates for the trials were scheduled between days 1-12 of the follicular phase of each volunteer's menstrual cycle. Each volunteer completed a $\dot{V}O_{2PEAK}$ test, DEXA scan, 4 whole body scans and 3 cold chamber trials. To estimate the sample size needed for the study, power calculations were performed for core temperature (T_{PILL}), mean skin temperature (T_{SK}) and heat flux (HF). Table 1 gives the sample size justification for the outcome variables and Table 2 provides the volunteer characteristics.

Each volunteer was recruited to fit medium size clothing and during the orientation sessions all volunteers had the opportunity to make sure the clothing fit properly.

The women in this study had a mean age (± SD) of 33.9 (5.7), mean height of 1.65 m (0.08), and a mean weight of 57.1 kg (6.2). Six of the women were in follicular phase of the menstrual cycle and the remaining 4 had amenorrhea.

2.2.3. Instrumentation

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

Each volunteer wore a facemask connected to a flow sensor to assess their ventilation and from which expired gases where drawn and analyzed with a breath-by-breath metabolic cart (COSMED USA Inc., Chicago, USA). Prior to each trial the flow sensor was calibrated for volume using a 3L syringe and two gas tanks one with 16% O_2, 5% CO_2, and 79% N_2 and the other with 26% O_2, balance N_2 were used to calibrate the gas sensors of the metabolic cart. All of these calibrations were performed at room temperature of ~ 22°C and relative humidity of ~40%. HR was recorded using a Polar HR monitor (Polar Electro V800, Kempele, Finland) and thorax strap and core temperature was collected by a pill (T_{PILL}) ingested 3 hours prior to the test (VitalSense, Bend, USA).

Climate Chamber, Skin and Core Temperature, Surface Heat Flux and Microclimate

All jacket trials took place in a climatic chamber (643399-00D, Weiss Envirotronics Inc, Santa Clara, USA). The volunteer was instrumented with 8 heat flux disks (Figure 2.1) with integral skin temperature thermistors (FR-025-TH44018-F20, Concept Engineering, Old Saybrook, USA) on the upper body to measure heat flux. These locations included the anterior shoulder, thorax, abdomen, upper arm, lower arm, upper back, lower back, and wrist.

To measure temperature and relative humidity of the microclimate between the base layer and jacket, each volunteer was instrumented with 4 iButtons (DS1904L-F5# iButton, Maxim Integrated Products, Whitewater, USA) with one iButton on the upper and lower thorax and one iButton on the upper and lower back (Figure 2.2). The four iButtons were calibrated for temperature and RH. Temperature calibrations were conducted by placing each iButton on the top of a copper cylinder under a foam layer.

The cylinder was connected to a controlled temperature water bath (VWR Int, Model 1196, West Chester, Penn USA . A traceable platinum thermometer (Fisher Scientific, Nepean, ON, Canada) was used to record temperatures at the site of the iButton after the water bath stabilized for 60 min at temperatures close to 15°C, 20°C, 25°C, 30°C, 35°C, and 40°C. To calibrate RH, each iButton was suspended above 4 different saturated salt solutions for 90 min. The salt solutions included LiCl that gave an RH of 11%, MgCl that gave an RH of 33%, NaCl that gave an RH of 75%, and K_2SO_4 that gave an RH of 97%. Linear regression plots were completed for the iButton temperatures vs. traceable platinum thermometer and iButton vs. Salt RH. Significant positive correlations (r) between the platinum thermometer temperatures and iButton temperatures were evident with r values of 1.0 for each iButton ($p<0.05$). The r values between the salt solution RH and the iButton RH were $0.995 < r < 0.997$ with $0.003 < p < 0.04$.

Thermistors 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). Heart rate was recorded using a Polar HR monitor (Polar Electro V800, Kempele, Finland) and thorax strap. Core temperature was collected using a pill (T_{PILL}) ingested 3 hours prior to the test (VitalSense, Bend, USA).

Heat flux disks with integrated thermistors were calibrated for heat flux and temperature using an insulated, copper cylinder fed by temperature controlled water bath (VWR Int, Model 1196, West Chester, Penn USA) for a heat flux range between -5 and -110 $W \bullet m^{-2}$.

Each volunteer's body mass was measured using a scale (Seca Model 515/514, Hamburg, Germany) before and after each chamber trial. Height was measured before the first trial using an electronic stadiometer (Seca stadiometer Model 264, Hamburg, Germany).

Body Scans

Body composition of each volunteer was determined with a dual energy X-ray absorptiometry (DEXA) scanner (S/N- 81867, Hologic Inc, Bedform, USA). Body surface area was also measured using a 3-D body scanner (Anthroscan, Cary, USA).

Technical Apparel

Each volunteer wore the same base layer in each cold trial that included a long sleeve top, tights, socks, sports bra and underwear in the preferred sizes (Table 2-3A). Three jackets employed in the study included Jacket 1 with its regional fabric thermal resistance values placed in an inverse proportion to previously reported T_{SK} (Figure 2-3), Jacket 2 with its regional fabric thermal resistance values placed in a direct proportion to previously reported T_{SK} (Figure 2.4), and a Control Jacket of consistent fabric thermal resistance (Figure 2-5). The pattern of fabric thermal resistance was varied for Jackets 1 and 2, but constant for the Control Jacket. The conductive/convective and evaporative resistance for the base layer clothing can be found in Table 2-3A. The conductive/convective and evaporative resistances for each of the 3 jackets as well as the calculation for the $R_{CT\ TOTAL}$ for each jacket is given in Table 2-3B. The jackets were not washed in order to prevent any changes to the thermal resistance values.

2.2.4. Data Acquisition

The $\dot{V}O_{2PEAK}$ test was performed on a treadmill while collecting expired gases with a breath-by-breath metabolic cart (COSMED USA Inc., Chicago, USA). Heart rate was recorded by telemetry using a Polar HR monitor (Polar Electro V800, Kempele, Finland). Skin temperature and surface heat flux were collected using heat flux transducer disks with integral skin temperature thermistors (FR-025-TH44018-F20, Concept Engineering, Old Saybrook, USA). The heat flux disk used two thermocouples, which monitor the temperature gradient in order to determine the direction and magnitude of heat flow. This measurement was recorded every 5 s to a data acquisition system connected to a computer utilizing LabVIEW software (Ver. 7.1, National Instruments, Austin, TX, USA). Core temperature was recorded using an ingestible radiotelemetry temperature pill, which transmitted a signal every 15 s to the VitalSense monitor (VitalSense, Bend, USA). iButton’s (DS1904L-F5# iButton, Maxim Integrated Products, Whitewater, USA) recorded microclimate temperature and RH between the base layer of clothing and the jacket at a 5 s sampling rate. The iButton data was downloaded at the end of each trial. All physiological data was recorded manually on a data sheet every 3 min and kept in a binder. All the hand recorded physiological data were then transferred to a spreadsheet on a computer.

2.2.5. Protocol

$\dot{V}O2_{PEAK}$ Test

Each volunteer performed an incremental exercise test from rest to the point of exhaustion on treadmill to determine $\dot{V}O_{2PEAK}$. Upon arrival the volunteer read and signed an informed consent. The volunteer's height and weight was then measured. An 8-10 min warm up on the treadmill was executed prior to the $\dot{V}O_{2PEAK}$ test. The protocol for the test increased speed by 1 km/h each minute starting at 6 km/h until reaching 11 km/h on the treadmill. Once the speed had been reached, the grade of the treadmill will increase by 2% each minute. Termination of the test occurred once the volunteer reached a steady age-predicted maximal HR, a respiratory exchange ratio (RER) of 1.15 unitless, or a plateau in rate of consumed oxygen ($\dot{V}O_2$). Due to the nature of a maximal test, the volunteers were made aware of symptoms to be expected and informed, if necessary, the test could be terminated prior to reaching $\dot{V}O_{2PEAK}$. A harness was worn throughout the duration of the test as a safety precaution.

Cold Climatic Chamber Trials

The performance of each jacket was assessed during three separate 55 min sessions (Table 2.4) at an exercise intensity 10% below their pre-determined ventilatory threshold; the method for determining these thresholds is given below in the Statistical Analyses section. On three separate days, three trials were conducted in the climatic chamber at a dry bulb temperature of -4°C with a RH of 50% to test the three jacket designs. During the running stages, but not at rest, a fan set at a velocity of ~1.7 m/s was used to simulate running speed on the treadmill.

2.2.6. Statistical Analysis

The physiological outcome variables included surface HF, T_{SK}, $T_{PILL,}$ MC_{RH} and MC_{TEMP}. A 2-way repeated measures ANOVA was utilized with factors of Jacket Type (1, 2 and Control) and Environmental Stage (Rest Stage I, Warm up and Exercise Stage I, Rest Stage II, Exercise Stage II).

Prior to the climatic chamber trials, the ventilatory threshold from the $\dot{V}O_{2PEAK}$ test for each volunteer was determined using Vieth's method (Vieth, 1985). Ventilatory equivalent for oxygen ($V_E/\dot{V}O_2$) was plotted as a function of the volume of consumed oxygen ($\dot{V}O_2$) from the incremental $\dot{V}O_{2PEAK}$ test. This is an iterative method that fits two linear regression functions to the data to estimate where the first regression line intersects with the second regression line; the threshold is at the point with a minimized residual sum of squares for the 2 regression lines.

During the trials the intensity at which each volunteer exercised was the HR at 10% below the value corresponding to the ventilatory threshold. The Vieth threshold detection method was calculated with code written in LabVIEW (Ver. 7.1, National Instruments, Austin, TX, USA). Results were considered statistically significance if $p<0.05$.

2.3. Results

Women's anthropometric and physiological characteristics are given in Table 2-2. There was no evidence of a main effect of Jacket Type for T_{PILL}, however, there was a significant interaction between Jacket Type and Time for mean T_{PILL} ($p=0.002$). During Rest Stage II and Exercise Stage II T_{PILL} was significantly less for Jacket 2 versus the Control Jacket (Figure 2-6). For Mean 8-site T_{SK} (Figure 2-7), Mean 8-site surface HF (Figure 2-8) and mean 4-site MC_{RH} (Figure 2-9A), there were no differences between the 3 jacket designs. There was a significant main effect of Jacket Type ($p=0.049$) and a significant interaction between Jacket Type and Time for mean 4-site MC_{TEMP} and this was explained by Jacket 2 giving temperatures significantly higher than for Jacket 1 and closer to a thermonuetral T_{SK} of 28°C (Figure 2-9B). The Jacket 1 Mean 4-Site MC_{TEMP} was the furthest of the 3 Jackets from a thermonuetral T_{SK} of 28°C at each of these comparison points

Regional T_{SK} for Shoulder (Figure 2-10A) and Abdomen (Figure 2-10C) showed no significant differences between the 3 jackets, yet an interaction ($p<0.01$) between Jacket Type and Time was evident for T_{SK} Thorax (Figure 2-10B; $p=0.005$) and Upper Arm T_{SK} (Figure 2-11D; $p=0.004$). During Exercise Stage II, Jacket 1 Thorax T_{SK} value was less than that for the Jacket 2 and Control Jacket, whereas for Jacket 1 the upper arm T_{SK} was greater than those for Jacket 2 and the Control Jacket. Lower arm (Figure 2-11E), wrist (Figure 2-11F), as well as lower back T_{SK} (Figure 2-12H) displayed no differences, but for upper back T_{SK} (Figure 2-12G) there was a significant main effect of Jacket Types ($p=0.018$) and a significant interaction of Jacket Type and Time ($p=0.004$). The difference existed with Jacket 1 having lower T_{SK} by ~1.5°C than Jacket 2 for the majority of the cold chamber trial. For Jacket 2 Upper Back T_{SK} was significantly lower during Exercise Stage I and onset of Rest Stage II relative to the Control Jacket, where Jacket 1 T_{SK} was ~0.5°C lower than the Control Jacket.

Assessing regional HF for shoulder (Figure 2-13A) and abdomen (Figure 2-13C) did not show significance between jacket types, but for the thorax HF (Figure 2-13B) a significant interaction between Jacket Type and Time was evident ($p=0.019$). This was explained by Jacket 1 with the most negative HF of ~-150 W/m^2, which remained more negative than the Control Jacket ($p<0.05$) during both exercise stages. Upper Arm HF (Figure 2-16D) showed no differences between jackets but Wrist HF (Figure 2-16F) showed a trend for a Jacket Type and Time interaction ($p=0.078$) with Jacket 1 giving the least negative HF of ~ 70 to -80 W/m^2 relative to Jacket 2 and the Control Jacket. For Lower Arm HF (Figure 2-14E) there was both a significant main effect of Jacket Type ($p=0.025$) and a significant interaction term between Jacket Type and Time ($p=0.043$). Jacket 1 had a significantly less negative HF than Jacket 2 for Lower Arm across all stages of the trial and this difference was ~-40 W/m^2 during the exercise stages. Upper back HF (Figure 2-15G) was significant for the main effect of Jacket Type ($p<0.001$) and for Jacket Type by Time interaction term ($p<0.001$). Jacket 1 HF was more negative than Jacket 2 HF across the exercise and rest stages in the climatic chamber ($p<0.05$), Lower Back HF showed no evidence of a significant difference between Jacket Types (Figure 2-15H).

There was no effect of the Jacket Type nor a Jacket Type by Time interaction for MC_{RH} and MC_{TEMP} for the Upper Front (Figure 2-16 A and B), Lower Front (Figure 2-17 A and B) and, Upper Back (Figure 2-18 A and B). As well there was no effect of Jacket Type or Jacket Type by Time interaction for Lower Back MC_{RH} (Figure 2-19A). There was a main effect of Jacket Type ($p=0.009$) and Jacket Type by Time Interaction ($p=0.002$) for Lower Back MC_{TEMP} due to significant differences between Jacket 1 and 2 (Figure 2-19B), where Jacket 1 had significantly lower MC_{TEMP} than both Jacket 2 and the Control Jacket across all exercise stages.

2.4. Discussion

A main novel finding of the study is for jackets that have the same total fabric thermal resistance but varied locations of the regional fabric thermal resistance, if only whole body physiological responses are measured, the study results would be largely unapparent. The mean 8-site surface T_{SK} and mean 8-site surface HF responses, as was the case for the majority of the microclimate assessments, did not show a difference between the 3 jacket designs (Figures 2-7 to 2-8, 2-10 to 2-11). The two exceptions for whole body physiological response were: i) core temperature or T_{PILL} (Figure 2-6) responded more slowly in Jacket 2 relative to the Control Jacket and this may have contributed to a better TC, and ii), 4-site MC_{TEMP} in Jacket 1 was significantly lower than Jacket 2

The second group of novel findings in the study is reflected by the novel jacket designs influences on regional physiological responses, as given in the next sections. All volunteers ran at the corresponding HR 10% below ventilatory threshold was used to monitor the intensity at which the volunteers ran. This intensity was selected in order to allow for the volunteers to have a similar sustainable level of exertion so as to prevent them from fatiguing during the trial. Wind velocity of 1.7 m/s = 6.1 km/h was used for each volunteer for each trial, so as to emulates a training run.

2.4.1. Regional Physiological Responses

If more or less fabric thermal resistance is put over body surface areas previously reported to have high or low T_{SK}, will this move T_{SK} in a direction that gives better physiology, that is temperatures closer to what would give a better TC vote? Holmér's IREQ scale supports that thermoneutral TC votes will be given when T_{SK} are closer to 28°C. As such, in the site by site analysis for regional physiological responses, an assessment was made for which jackets at a given body surface measurement site gave T_{SK} values closest to 28°C.

For the regional physiology responses, the discussion below is grouped by sites for Jackets 1 and 2 where they had the same R_{CT} at the measurement site, when Jacket 1 had lower R_{CT} at the measurement site than Jacket 2 and when Jacket 1 had greater R_{CT} at the measurement site than Jacket 2. Based on these differences a comparison is made of the expected regional T_{SK} and HF responses between Jacket 1 and 2. The expected direction of regional T_{SK} and heat flux HF for Jacket 1 compared to Jacket 2 are given in Table 2-5.

(a) Shoulder, Upper Arm and Lower Back Physiological Responses

For shoulder, upper arm and lower back, at each of these 3 measurement sites for T_{SK} and HF, each of the 3 jackets had the same R_{CT} value of 132 $m^2 \cdot K \cdot W^{-1} \cdot 10^{-1}$, consequently the physiological responses were expected to be the same. The results largely support this reasoning as Shoulder, Upper Arm and Lower Back T_{SK} (Figures 2-10A, 2-11D and 2-12H) and HF (Figures 2-13A, 2-14D and 2-15G) responses were largely the same with no differing responses at this measurement site with the exception of Upper Arm T_{SK} where Jacket 2 had a lower T_{SK} than the Control Jacket in the second exercise stage. As such, the results at these 3 measurement sites mostly support that the same fabric thermal resistance placed over the surface of the body gives the same physiological responses at that measurement site.

(b) Thorax and Upper Back Physiological Responses

At the Thorax and Upper Back measurement sites for T_{SK} and HF, Jacket 1 had a lower R_{CT} of 77 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-1}$ relative to that in Jacket 2 of R_{CT} of 185 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-1}$. This supports lower T_{SK} values and higher HF would be evident in Jacket 1 relative to Jacket 2. The results support this view in that Jacket 1 T_{SK} was lower than Jacket 2 T_{SK} both on the Thorax and on the Upper Back (Figures 2-10 and 2-12). The Upper Back T_{SK} dropped almost a full degree lower in Jacket 1 versus Jacket 2 although this same difference between the two jackets was not as pronounced on the thorax. For Jacket 1 both the Thorax and Upper Back T_{SK} values were closer to 28°C than Jacket 2 or the Control Jacket. Heat Flux on the Thorax and Upper Back (Figures 2-13B and 2-15G), as expected, was significantly more negative for Jacket 1 versus Jacket 2. This was especially apparent for the Upper Back HF where at points it was ~ 40 W/m^2 more negative in Jacket 1 versus Jacket 2. Largely, the physiological responses follow what was expected for the varied amounts of fabric thermal resistance at these two measurement sites for Jacket 1 and 2.

(c) Abdomen, Lower Arm and Wrist Physiological Responses

The remaining 3 surface measurement sites of the Abdomen, Lower Arm and Wrist had greater fabric thermal resistance in Jacket 1 versus Jacket 2. For the Abdomen Jacket 1 had a higher R_{CT} of 185 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-1}$ relative to that in Jacket 2 with a R_{CT} of 132 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-1}$. For the Lower Arm and Wrist Jacket 1 had a higher R_{CT} of 185 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-1}$ relative to that in Jacket 2 of R_{CT} of 77 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-1}$. For each of these sites this supports higher T_{SK} values and lower HF would be evident in Jacket 1 relative to Jacket 2.

Despite the jacket fabric R_{CT} differences, Abdomen T_{SK} (Figure 2-10C) and HF (Figure 2-13C) did not differ between the Jackets types. As well, for the Lower Arm and Wrist, although T_{SK} responses appear to be the greatest in Jacket 1 that had the highest fabric R_{CT}, there were no significant differences between jacket types for T_{SK} at this measurement site (Figures 2-11E and 2-11F). Although Abdomen HF was not different between the Jackets (Figure 2-13C), HF for the Lower Arm and Wrist in Jacket 1 was significantly less negative than in Jacket 2 and this supports placing a fabric with a greater R_{CT} at these measurement sites were effective at reducing heat loss at these sites (Figures 2-14E and 2-11F).

The results above support the hypothesis that when varying the placement of fabric thermal resistance in a winter jacket, it will perform differently physiologically than a jacket with consistent thermal fabric resistance. For mean 8-site $T_{SK,}$ 6 of 8 and for mean 8-site HF, 7 of 8 measurements sites gave changes in regional T_{SK} and HF as expected from the differences in overlying fabric thermal resistance. How these physiological variables relate to Thermal Comfort is addressed in Chapter 3.

2.4.2. Microclimate Responses

A main effect of Jacket Type and an interaction for Jacket Type and Time was evident for mean 4-site MC_{TEMP} (Figure 2-9B) and for Lower Back MC_{TEMP} (Figure 2-19B), where Jacket 1 with more fabric thermal resistance over areas of low T_{SK} resulted in the reduced Lower Back MC_{TEMP} as compared to either just Jacket 2 or the Jacket 2 and the Control Jacket. The reduced 4-site MC_{TEMP} for Jacket 1 may be an influencing factor on the T_{SK} responses for Jacket 1 resulting in values closer to the thermoneutral T_{SK} of 28°C. The support for this view, however, is weak since mean 4-site MC_{TEMP} for Jacket 1 was the lowest at ~23-24°C and further from a thermoneutral T_{SK} of 28°C than either Jacket 2 or the Control Jacket (Figure 2-9B).

2.4.3. Comparison to the Literature

There is limited research assessing physiological and TC responses to varied placement of fabric thermal resistance in winter garments. Assessments of body-mapped sportswear have been studied in hot environments for both human and thermal manikin trials (Wang, Del Ferraro, Molinaro, Morrissey, & Rossi, 2014) (Jiao et al., 2017) (Wang et al. 2014), but studies of similar jacket designs for the cold, as those assessed in this study, were not uncovered in an exhaustive literature review. Nielsen & Nielsen (Nielsen & Nielsen, 1984) found during light cycle ergometer exercise of 35 W at 10°C ambient temperature, that a greater clothing insulation on the chest and abdomen, as compared to that on the arms, maintained a higher core temperature during exercise and rest (Nielsen & Nielsen, 1984). This was not evident in the current findings as for Jacket 2, with more fabric thermal resistance around the torso than the Control Jacket, gave a lower T_{PILL} responses exercise as compared to the Control Jacket. Comparisons between the two studies are difficult and this could be due to the varied insulation across the arms affecting vasoconstrictive responses to the cold, or due to the differences in the clothing insulation values between the studies. This response may have also been observed due to the difference in ambient temperature, -4°C vs 10°C, as well as the presence of fans in the current study and different modes of exercise in the two studies.

No observed differences between regional T_{SK} or HF were apparent at the abdomen measurement site between all 3 jackets. The use of the fan may have disturbed the layer of still air within the garment as well as compressed the fabric over the abdominal site. As suggested by Havenith, wind can reduce the thickness of insulation and effect the thermal properties (Havenith, 2003). Our results support this view due to no differences detected for T_{SK} and HF on the abdomen that was in direct line of the fan. Body mapping physiological responses including sweating and temperature sensitivity have continued to grow (Fournet et al., 2013; Gerrett et al., 2015; A. D. Smith, Crabtree, Bilzon, & Walsh, 2010). Our study did not observed variations between overall physiological responses for T_{SK} or HF between the jackets, but some regional differences were evident, supporting the importance of regional body mapping in clothing physiology. Smith & Havenith found sweat rates to be greater during exercise on the upper back as compared to the abdomen (C. J. Smith & Havenith, 2011). Although we did not measure sweat rates, the upper back for Jacket 1 contained less fabric thermal resistance, which corresponded with lower T_{SK} and higher HF. This could be due to the fabric with the lowest R_{CT} value being placed over the upper back, where there is a greater sweat rate, therefore allowing appropriate evaporative heat loss and reduced sweat accumulation, influencing T_{SK}.

2.4.4. Suggested Mechanism(s)

Effects of Varied Placement of Fabric Thermal Resistance on Jacket Performance in the Cold

Based on the findings of this study, the R_{CT} values of the fabrics are influencing the regional surface T_{SK} and surface HF values. This can be further explained using the concepts from Ohm's Law (Equation 2-1) where HF is proportional to the difference in temperature between the ambient air and skin temperature (ΔT) and inversely proportional to the total thermal resistance of the fabric (R_{CT}).

$HF = \Delta T/R_{CT}$……………………………………. Equation 2-1

Differences between J1 and J2 jacket designs that had the same R_{TOT} (Table 2-3), was due to varied patterns of fabric thermal resistance can be explained using Equation 2-1. The ΔT between jacket designs at a given T_{SK} measurement site were estimated to vary from ~29°C to 37ºC (Figures 2-10 - 2-12) and these are smaller compared to the absolute differences in regional R_{CT} (Δ $R_{CT\ J1-J2}$) between jacket designs 1 and 2, which were directional values between -108 to +108 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-3}$ (Table 2-5 and 2-6). Between jacket designs, on average the range of differences in regional R_{CT} approaches 2.2 times the ΔT at the regional locations between the jackets. For example, the average of -4°C - 29°C and -4°C - 37°C gives an average ΔT of ~ 37°C. Therefore an R_{CT} difference of 108 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-3}$ is much larger than the difference of ΔT at ~37°C. This supports that R_{CT} had a greater effect on a given HF than did regional differences of ΔT (Table 2-5).

Some limitations for the current study may include the time of day the volunteers were tested, as the trials were conducted from 8 am to 10 am or 10 am to 12 noon. A possible consequence of employing these two time slots in the study is potential circadian variation associated changes in core temperature in the results. In order to control for this, each volunteer was tested in the same time slot for all three trials and it should be noted that the circadian variation in core temperature in this time frame is small at ~ 0.2 to 0.3°C. There is also a limitation of the applicability of the results since the volunteers were only tested in the follicular phase. For future studies, the volunteers might be tested in both follicular and luteal phase to assess for differences between the jackets in each menstrual cycle phase. The benefit of studying the women in the follicular phase rather than in the luteal phase is due to less fluctuations of estradiol and progesterone hormone concentrations and thermoregulatory responses are more stable in the follicular phase (Stephenson & Kolka, 1985).

2.4.5. Conclusion

Hypothesis 2.1: It was hypothesized for the same cold condition of -4°C and the same moderate exercise intensity, that 2 jackets of similar total fabric thermal resistance that have their regional fabric conductive/convective thermal resistance values placed either in an inverse proportion (Jacket 1) or in a direct proportion (Jacket 2) to previously reported T_{SK} (Fournet et al., 2013), would elicit different physiological responses relative to a jacket of consistent overall fabric thermal resistance.

Response to Hypothesis 2.1 The evidence supports the first hypothesis that varying regional fabric thermal resistance placement either in an inverse proportion (Jacket 1) or in a direct proportion (Jacket 2) to previously reported T_{SK} (Fournet et al.,

2013) gave different physiological responses relative to a coat with consistent overall fabric thermal resistance.

Hypothesis 2.2: It was also hypothesized that Jacket 1, with its regional fabric thermal resistance values placed in an inverse proportion to previously reported T_{SK} (Fournet et al., 2013), would give better physiological responses than a jacket (Jacket 2) with it's fabric thermal resistance values placed in a direct proportion to previously reported T_{SK} (Fournet et al., 2013).

Response to Hypothesis 2.2: The hypothesis 2.2 was not accepted since few results supported Jacket 1 had better physiological responses than Jacket 2.

2.5. Tables

Table 2-1 Sample size justification for physiological variables with a power of 80% and an α-level set at 0.05

Outcome Variable	Difference in Mean Worth Detecting	Standard Deviation	Number of Participants
Core Temperature (°C)	0.3	0.3	10
Mean Skin Temp(°C)	1	0.75	7
Heat flux (W/m^2)	20	20	10

Table 2-2 Volunteer characteristics; values are the mean ±SD.

Vol. #	Age (y)	Height (m)	Weight (kg)	BMI (kg•m-2)	VO2PEAK (mL/min)	1Adiposity (%)	2Lean Mass (%)	3HRPEAK (b•min-1)	4HREXE (b•min-1)	5FDAY (d)
1	41	1.58	48.6	19.4	2154	31.3	68.7	195	140	5Am
2	23	1.71	65.6	22.3	2725	28.5	71.5	191	163	4-5-11
3	34	1.59	56.2	22.2	2427	28.0	72.0	174	135	2-9-11
4	36	1.60	52.7	20.7	2132	29.7	70.3	175	153	6-2-3
5	27	1.79	68.9	21.4	3342	20.7	79.3	182	144	5Am
6	37	1.59	54.4	21.5	2353	28.4	71.6	192	155	1-2-3
7	35	1.67	53.2	18.9	2912	19.7	80.3	191	159	8-10-4
8	36	1.66	55.4	19.9	2233	20.7	79.3	183	147	6-1-7
9	40	1.76	60.1	19.3	1700	21.2	78.8	170	146	5Am
10	30	1.57	56.0	22.7	2365	28.6	71.4	197	160	5Am
Mean	33.9	1.65	57.1	20.8	2434	25.7	74.3	185	150	
(SD)	(5.7)	(0.08)	(6.1)	(1.4)	(459.2)	(4.5)	(4.5)	(9.6)	(9.2)	-

Footnotes:

[1] Adiposity percentage from DEXA scans

[2] Lean tissue percentage includes bone mineral content and lean tissues from DEXA scan

[3] HR$_{EXER}$ is heart rate at 10% below the ventilation threshold

[4] Days in the follicular (F$_{DAY}$) phase for when trials for Jacket 1, Jacket 2 and the Control Jacket took place (e.g. 3-5-8)

[5] Amenorrhea (Am)

Table 2-3 **A) R_{CT}, R_{ET} values for base layers B) R_{CT}, R_{ET} Jacket values and calculations**

A)	$R_{CT\ TOTAL}$ ($m^2 \cdot K \cdot W^{-1} \cdot 10^{-3}$)	R_{ET} ($m^2 \cdot Pa \cdot W^{-1} \cdot 10^{-3}$)
Long sleeve Top	10	2.75
Sports Bra	6.1	2.9
Tights	5.5	1.8
Underwear[1]	-	-
Socks[1]	-	-

B)	Inner & Outer layer (R_{CT}) ($m^2 \cdot K \cdot W^{-1} \cdot 10^{-3}$)	Inner & Outer layer (R_{ET}) ($m^2 \cdot Pa \cdot W^{-1} \cdot 10^{-3}$)	[2]Yellow (W/K)	[2]Light Blue (W/K)	[2]Dark Blue (W/K)	[3]$R_{CT\ TOTAL}$ ($m^2 \cdot K \cdot W^{-1} \cdot 10^{-3}$)
Jacket 1	4	1.2	0.3433/185 = 0.001856	0.3101/132 = 0.002349	0.2919/77 = 0.003791	118.2
Jacket 2	4	1.2	0.1916/185 = 0.001036	0.5140/132 = 0.003894	0.2396/77 = 0.003111	117.5
Control Jacket	4	1.2	-	0.9453/132 = 0.007161	-	132.0

A) Conductive/convective dry resistance (R_{CT}) and Evaporative resistance (R_{ET}) values for the base layer garments. B) Calculations for total conductive/convective dry resistance (R_{CT}) values of the 3 Jackets. Conductive/convective dry resistance (R_{CT}) and Evaporative resistance (R_{ET}) for the inner and outer layers of the 3 material types are given. The total area of each Jacket is 0.9453 m^2

Footnotes:

[1] Values unknown

[2] Calculations of the contribution of a given material to $R_{CT\ TOTAL}$ is the relative area of that material in a given jacket divided by the R_{CT} value of that material.

[3] Calculation of R_{CT} TOTAL for the 3 materials in each of jacket 1 and 2 is with a calculation of total thermal resistance using parallel thermal resistance addition,

i.e. $1/R_{CT\ TOTAL} = (Area_{77}/R_{CT77} + Area_{132}/R_{CT132} + Area_{185}/ R_{CT185})$/total area

Table 2-4 Trial Stages

Stage	Rest Stage I	Warm-up Stage	Exercise Stage I	Rest Stage II	Exercise Stage II
Duration (min)	10	5	15	10	15
TDB (°C)	~22	- 4	- 4	- 4	-4
Posture	Seated	Submax. Running	Submax. Running	Standing	Submax. Running

Table 2-5 **Regional conductive/convective fabric thermal resistance values (R_{CT}, $m^2 \bullet K \bullet W^{-1} \bullet 10^{-3}$) in Jackets 1, 2 and the Control Jacket. The R_{CT} difference (ΔR_{CT}) is for Jacket 1 R_{CT} minus the Jacket 2 R_{CT}**

	Shoulder R_{CT}	Thorax R_{CT}	Abdomen R_{CT}	Upper Arm R_{CT}	Lower Arm R_{CT}	Wrist R_{CT}	Upper Back R_{CT}	Lower Back R_{CT}
Jacket 1	132	77	185	132	185	185	77	132
Jacket 2	132	185	132	132	77	77	185	132
Control	132	132	132	132	132	132	132	132
$\Delta R_{CT\ J1-J2}$	0	-108	53	0	108	108	-108	0

Table 2-6 The expected direction of regional skin temperatures (T_{SK}) and heat flux (HF) for Jacket 1 (J1) compared to Jacket 2 (J1). The symbols in the table are explained in the footnotes.

Region	Jacket 1 R_{CT} (m^2•K • W^{-1}•10^{-3})	Jacket 2 R_{CT} (m^2•K • W^{-1}•10^{-3})	ΔR_{CT} (m^2•K• W^{-1}•10^{-3})	Expected Direction T_{SK} J1 vs. J2	Expected Direction HF J1 vs. J2	Results for T_{SK}	Results for HF
Shoulder	132	132	0	↔	↔	✓	✓
Thorax	77	185	-108	↓	↑	✓	✓
Abdomen	185	132	53	↑	↓	?	?
Upper Arm	132	132	0	↔	↔	?	✓
Lower Arm	185	77	108	↑	↓	✓	✓
Wrist	185	77	108	↑	↓	✓	✓
Upper Back	77	185	-108	↓	↑	✓	✓
Lower Back	132	132	0	↔	↔	✓	✓

Footnotes:

↑ Jacket 1 was expected to have a greater response than Jacket 2

↓ Jacket 1 was expected to have a lower response than Jacket 2

↔ No difference in response was expected between Jacket 1 and 2

✓ Results followed the expected directions for T_{SK} or HF

? Results did not followed the expected directions

Torso fabric thermal resistance in Jacket 1 was a net of -163 m^2 • K • W^{-1} • 10^{-3} less than Jacket 2

Torso fabric thermal resistance in Jacket 2 was a net of 106 m^2 • K • W^{-1} • 10^{-3} greater than the Control Jacket

2.6. Figures

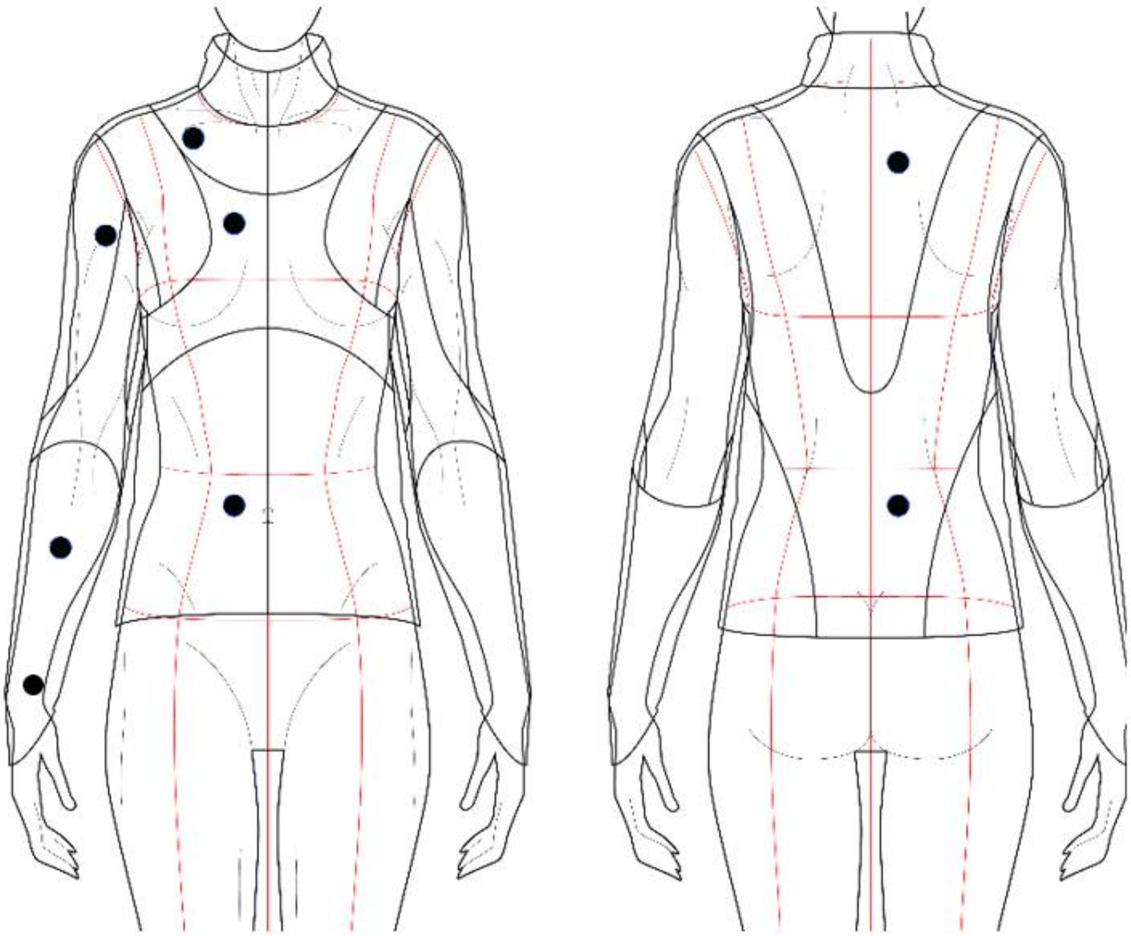


Figure 2-1 **Placement of heat flux disks on the skin to measure surface skin temperature and surface heat flux (black circles)**

Figure 2-2 Placement of four iButtons over the base layer and under the jacket (black circles)

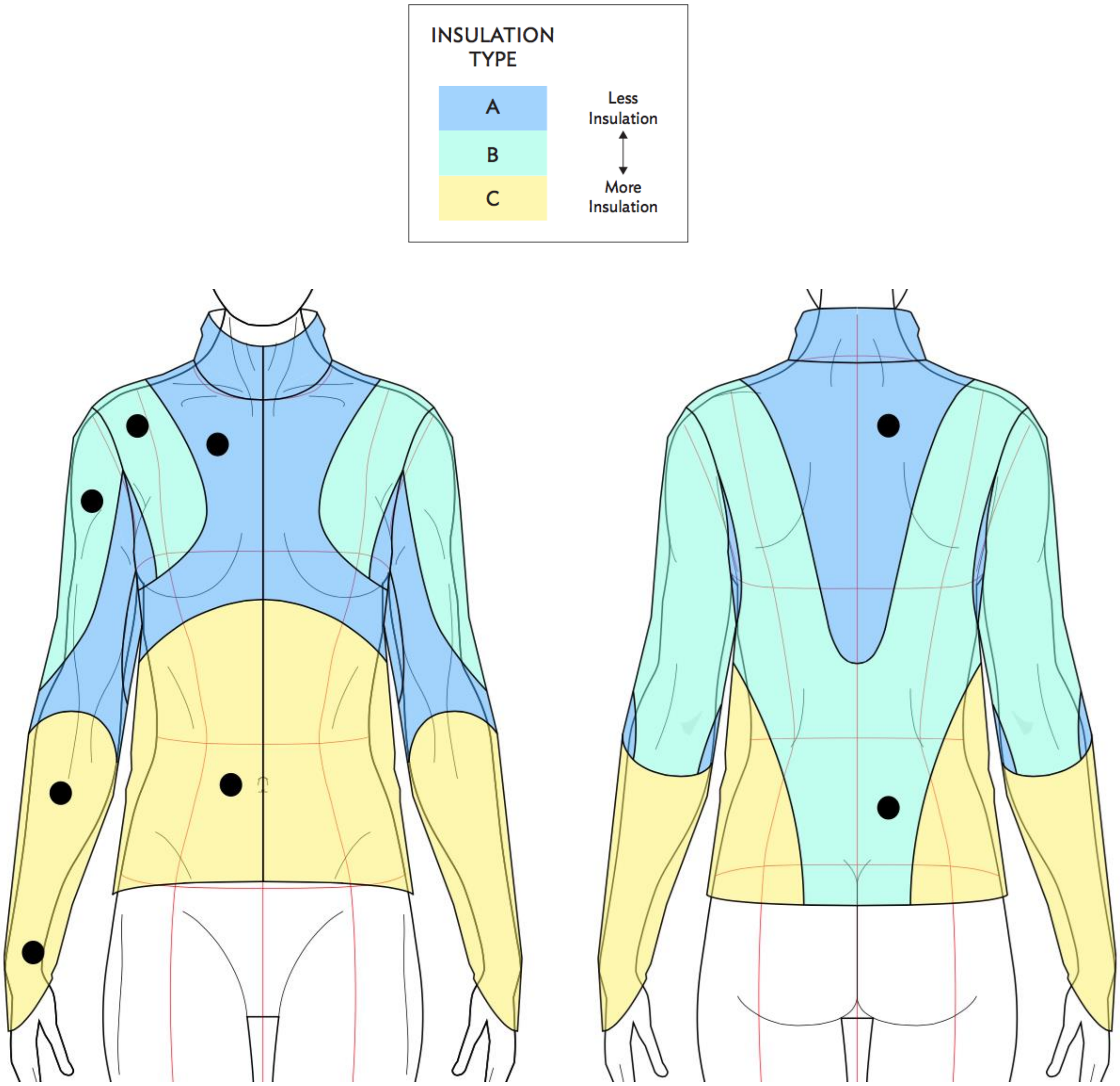


Figure 2-3 Mapping of resistance in Jacket 1.

The inner and outer layer of the jacket has a heat resistance (R_{CT}) value of 4 $m^2 \cdot K \cdot W^{-1} \cdot 10^{-3}$ and a vapour resistance (R_{ET}) value of 1.2 $m^2 \cdot Pa \cdot W^{-1}$. The fabric thermal resistance type A has an R_{CT} value of 77 $m^2 \cdot K \cdot W^{-1} \cdot 10^{-3}$, fabric thermal resistance type B has an R_{CT} value of 132 $m^2 \cdot K \cdot W^{-1} \cdot 10^{-3}$ and fabric thermal resistance type C has an R_{CT} value of 185 $m^2 \cdot K \cdot W^{-1} \cdot 10^{-3}$. Black filled circles indicate the placement on the upper body surface of heat flux disks with integral skin thermistors.

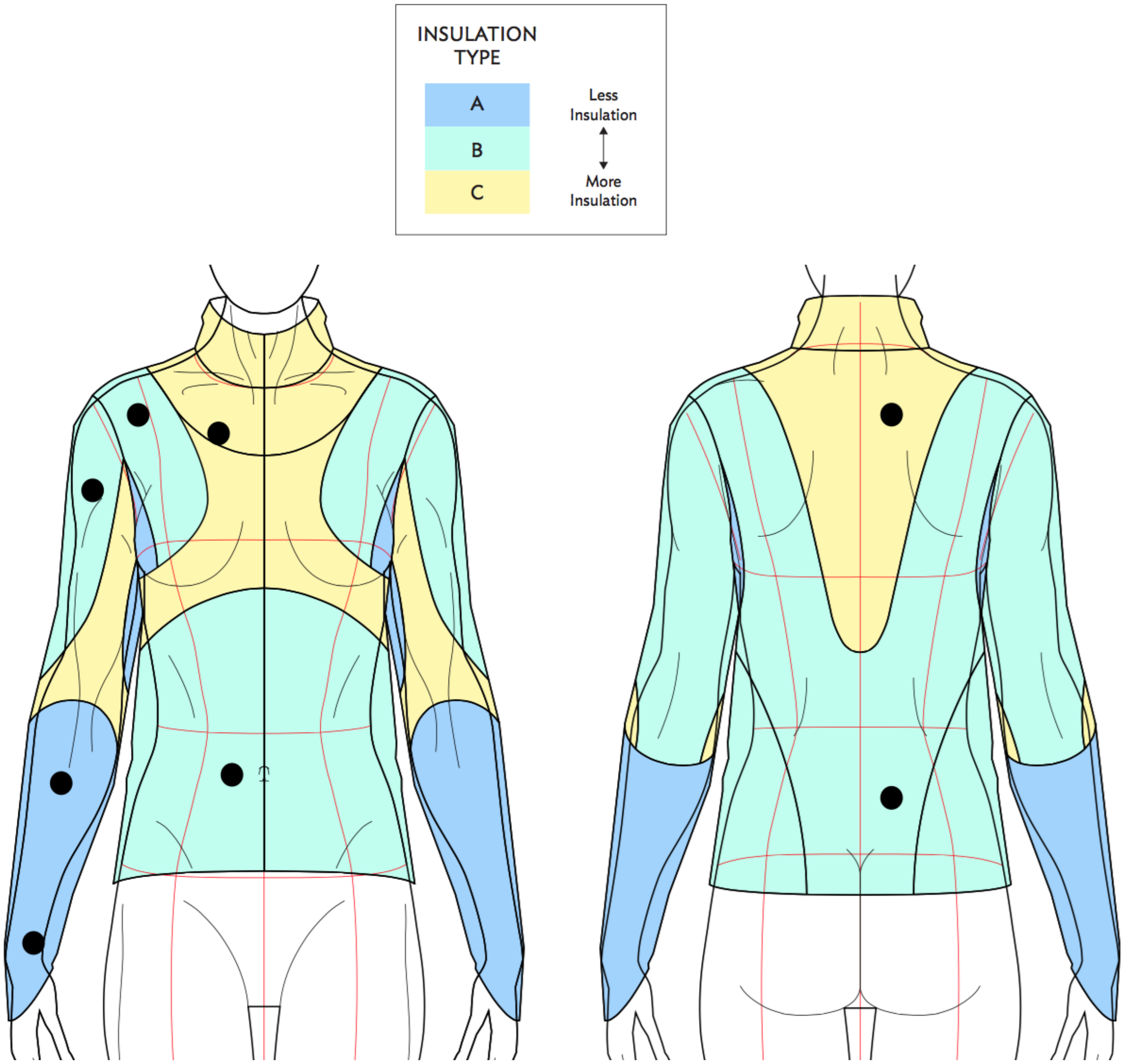


Figure 2-4 **Mapping of fabric thermal resistance in Jacket 2.**

The inner and outer layer of the jacket has a heat resistance (R_{CT}) value of 4 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-3}$ and a vapour resistance (R_{ET}) value of 1.2 $m^2 \bullet Pa \bullet W^{-1}$. The fabric thermal resistance type A has an R_{CT} value of 77 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-3}$, fabric thermal resistance type B has an R_{CT} value of 132 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-3}$ and fabric thermal resistance type C has an R_{CT} value of 185 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-3}$. Black filled circles indicate the placement on the upper body surface of heat flux disks with integral skin thermistors.

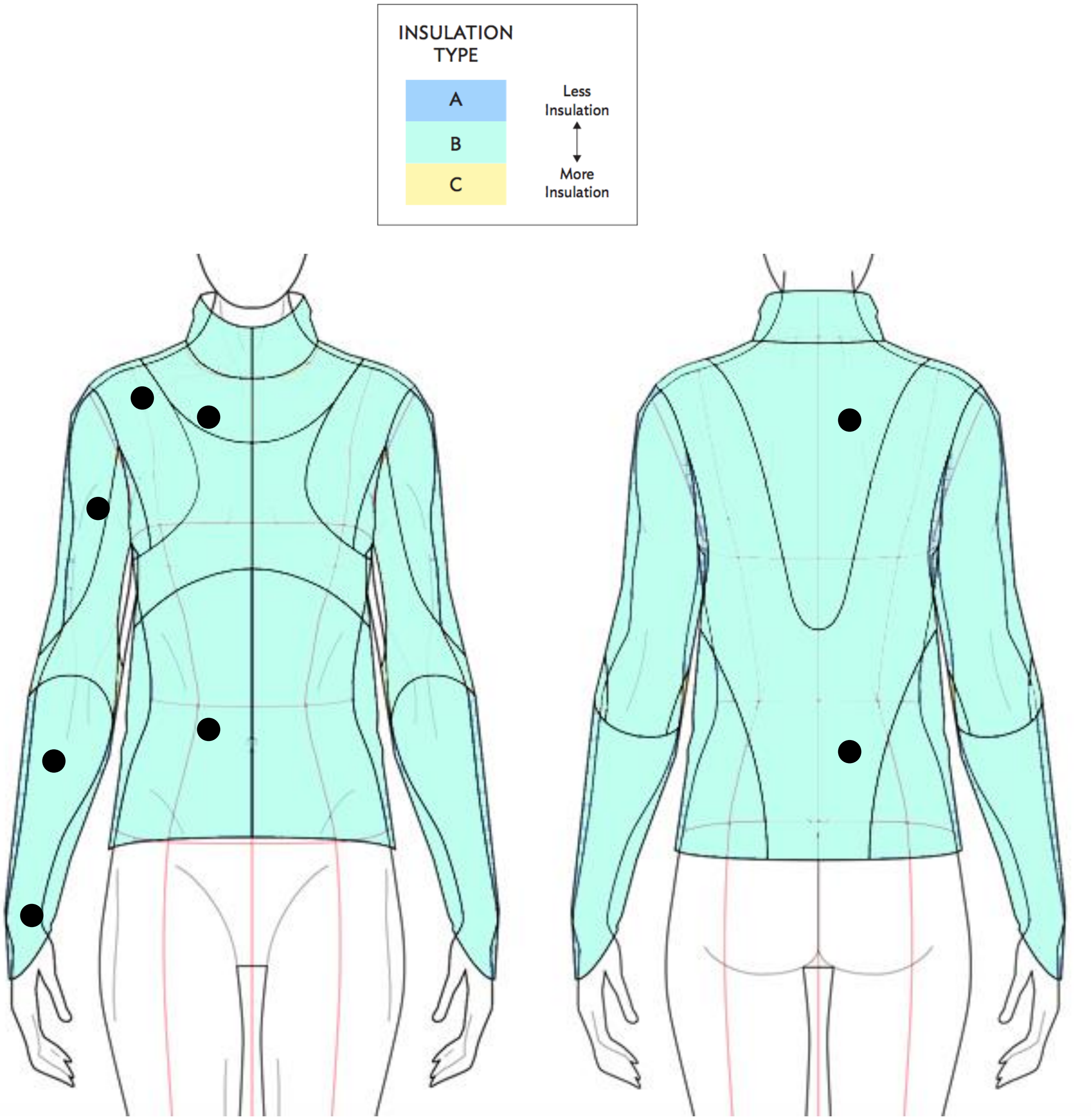


Figure 2-5 Mapping of fabric thermal resistance in Control Jacket.

The inner and outer layer of the jacket has an R_{CT} value of 4 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-3}$ and an R_{ET} value of 1.2 $m^2 \bullet Pa \bullet W^{-1}$. This gave an R_{CT} value of 132 $m^2 \bullet K \bullet W^{-1} \bullet 10^{-3}$ for Jacket 3. Black filled circles indicate the placement on the upper body surface of heat flux disks with integral skin.

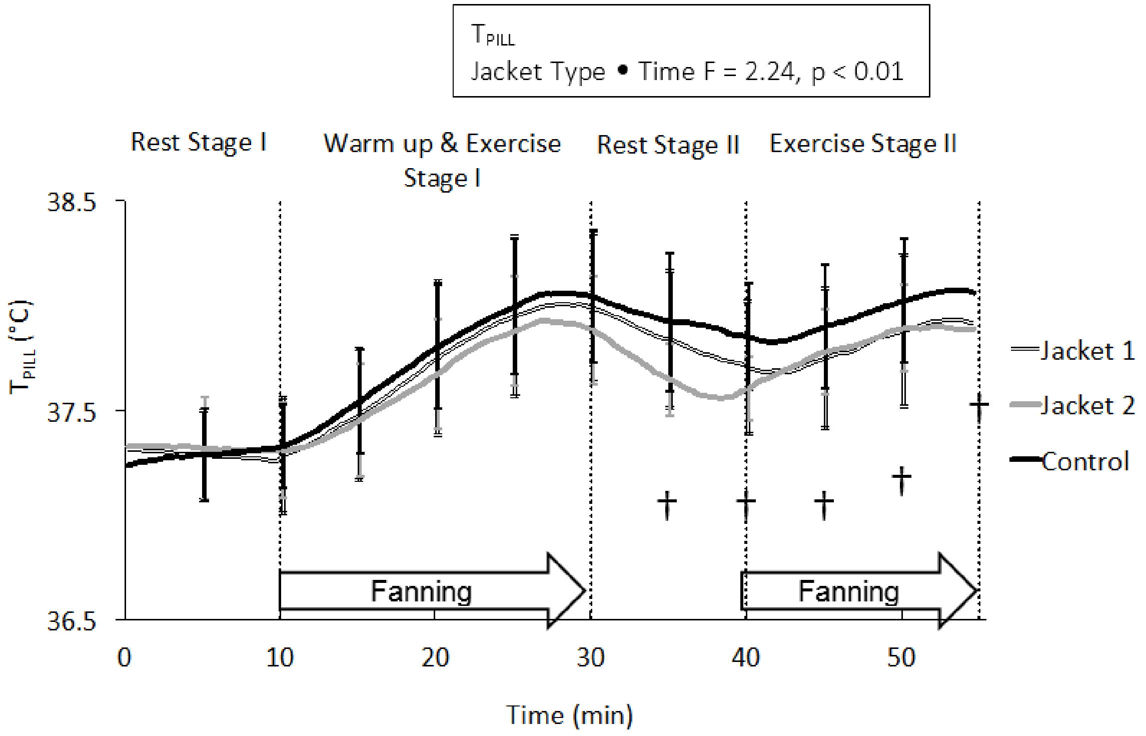


Figure 2-6 **Mean core temperature (°C) responses for each jacket type (n=10). The interaction between jacket type and time was significant; Jacket 1•2, * p<0.05; Jacket 1•Control, p<0.05; Jacket 2•Control, † p<0.05**

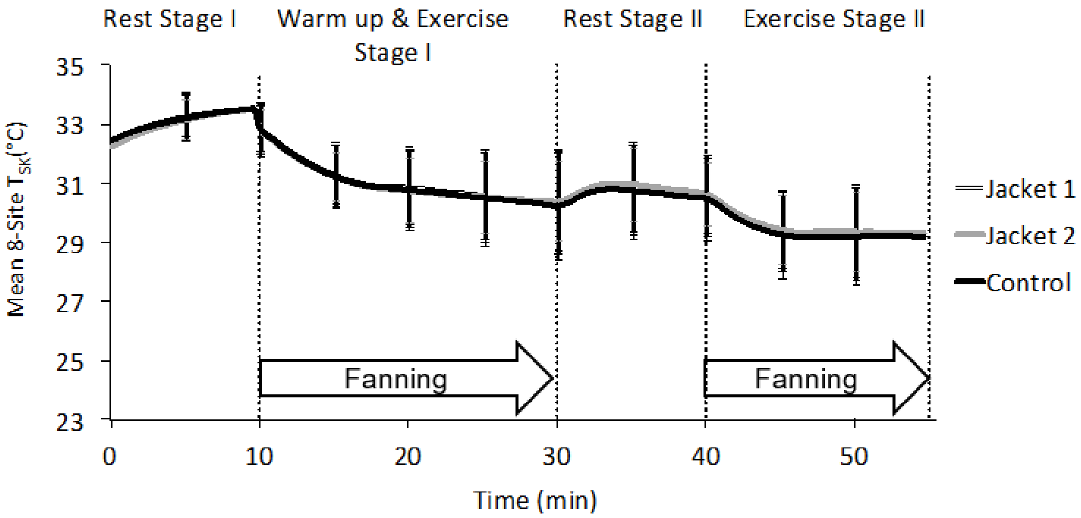


Figure 2-7 Mean 8-site skin temperature (°C) responses for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control, ♦ $p<0.05$; Jacket 2•Control, † $p<0.05$

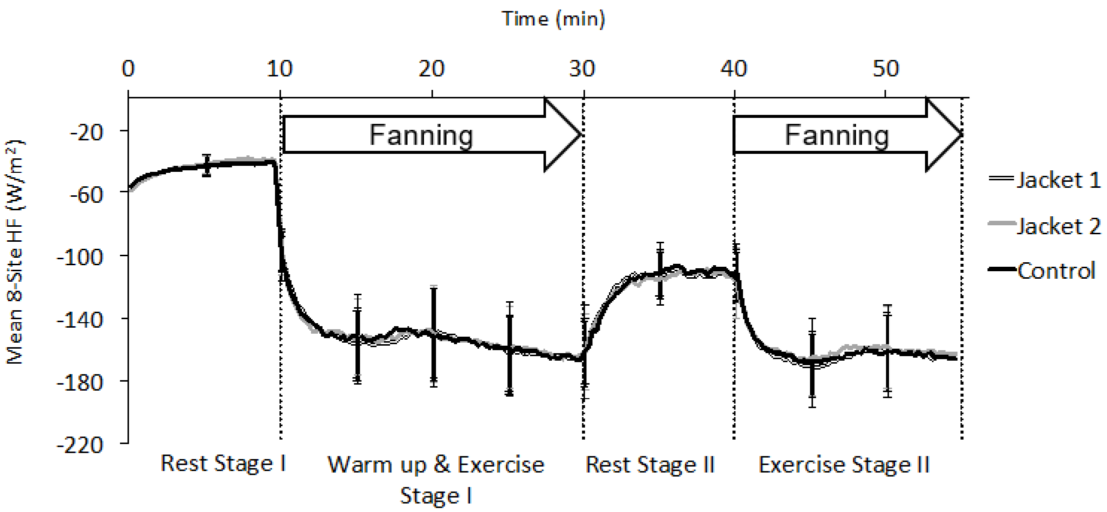
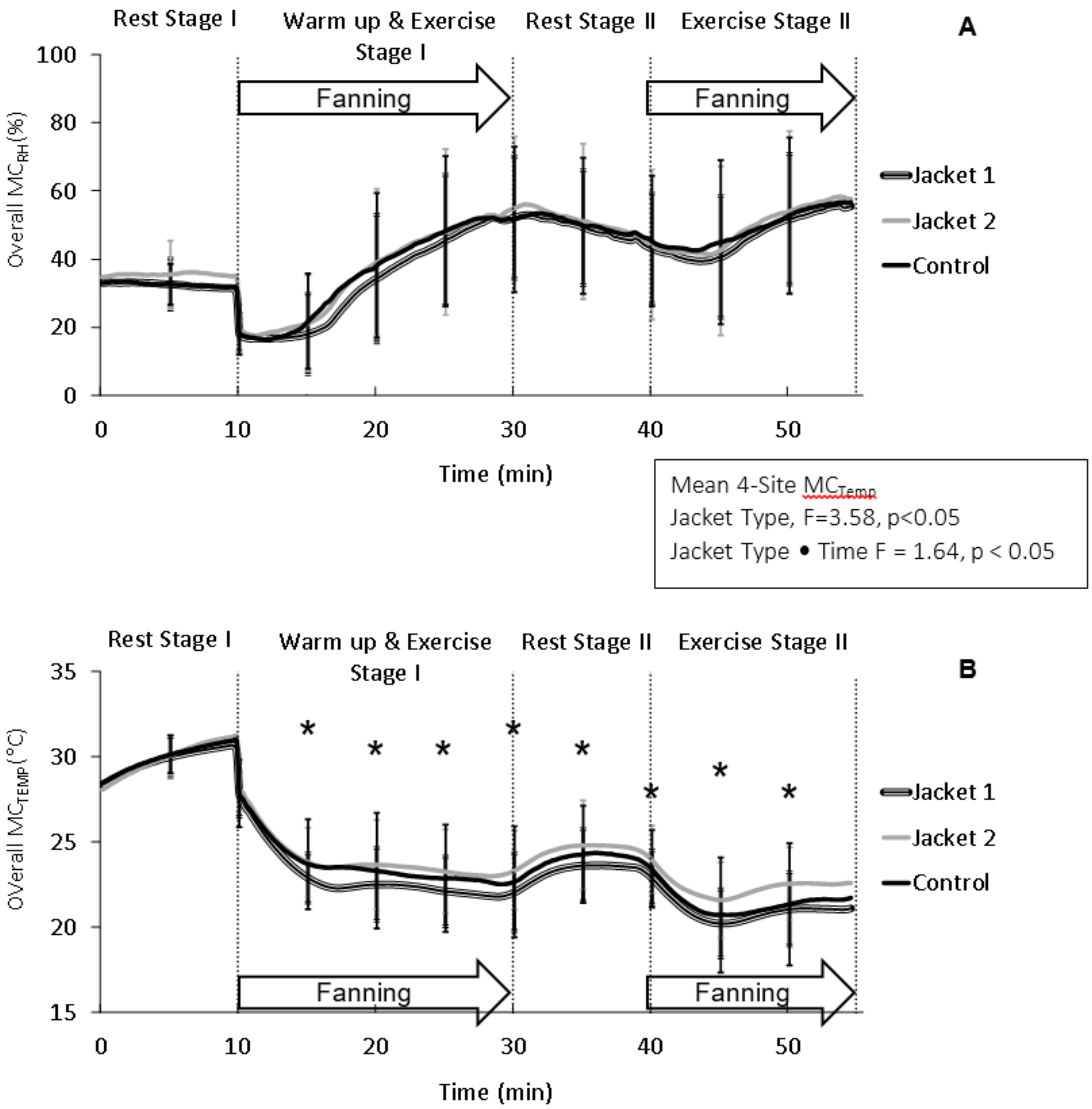


Figure 2-8 Mean 8-site surface heat flux (W/m2) responses for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control, ♦ $p<0.05$; Jacket 2•Control, † $p<0.05$



Mean 4-Site MC_{Temp}
Jacket Type, F=3.58, p<0.05
Jacket Type • Time F = 1.64, p < 0.05

Figure 2-9 **Mean 4-site microclimate RH (MC_{RH},%) (A) and Mean 4-site temperature (MC_{TEMP},°C) (B) response for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control, ♦ $p<0.05$; Jacket 2•Control, † $p<0.05$**

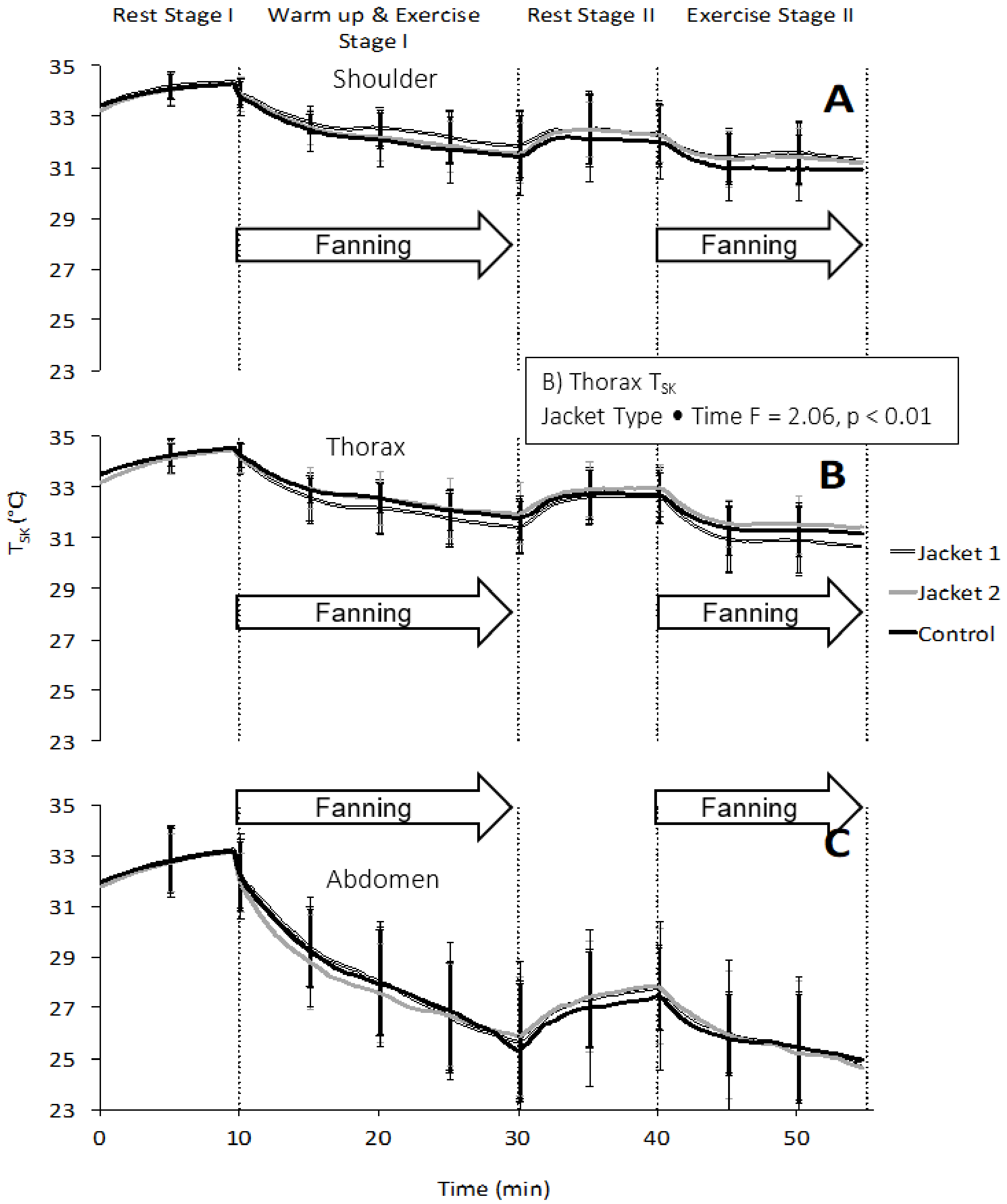


Figure 2-10 Mean skin temperature responses of (A) shoulder; (B) thorax; (C) abdomen for each jacket type (n=10); Jacket 1•2, * p<0.05; Jacket 1•Control, ◆ p<0.05; Jacket 2•Control, † p<0.05

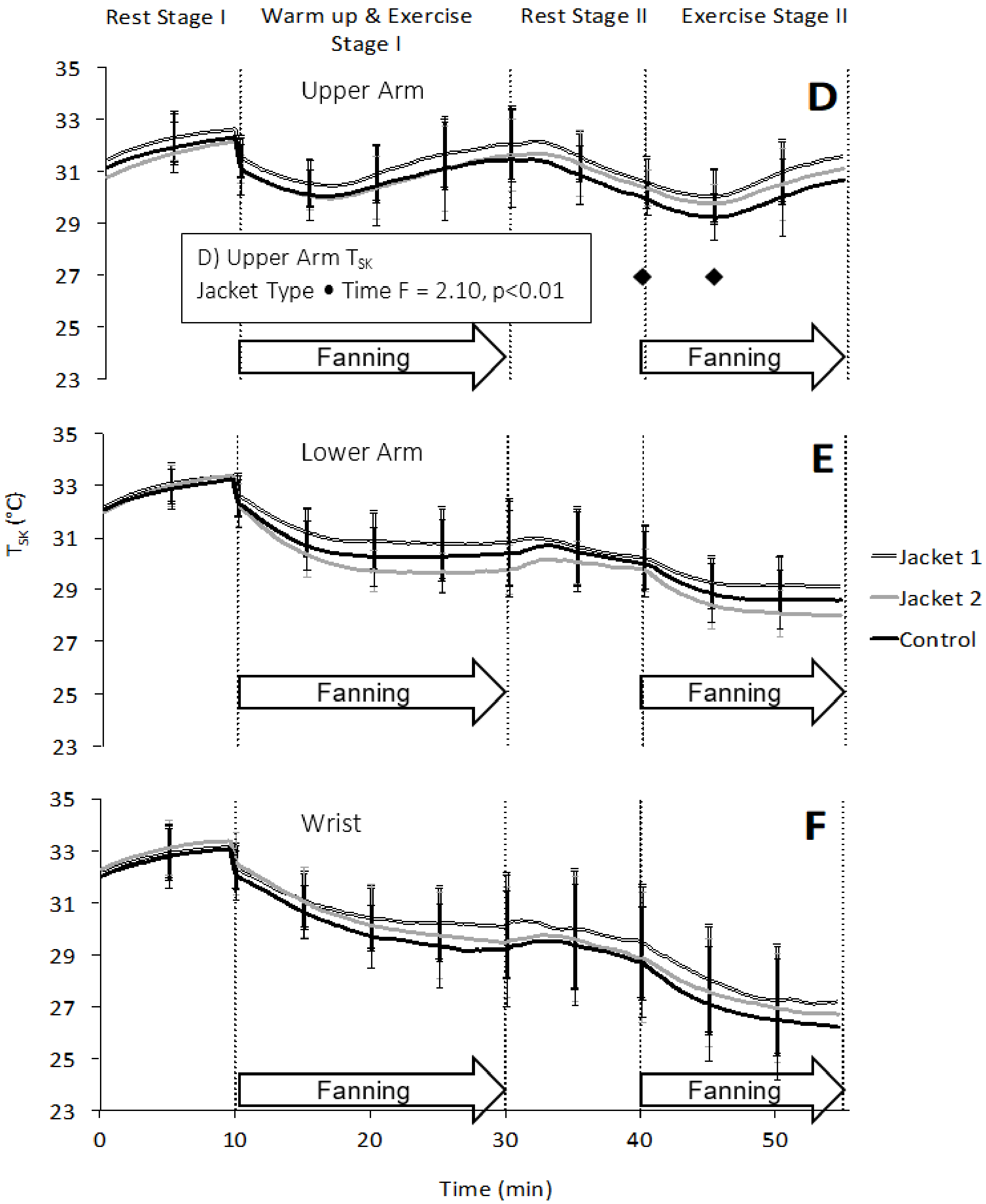


Figure 2-11 **Mean skin temperature responses of (D) upper arm; (E) lower arm; (F) wrist for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control, ◆ $p<0.05$; Jacket 2•Control, † $p<0.05$**

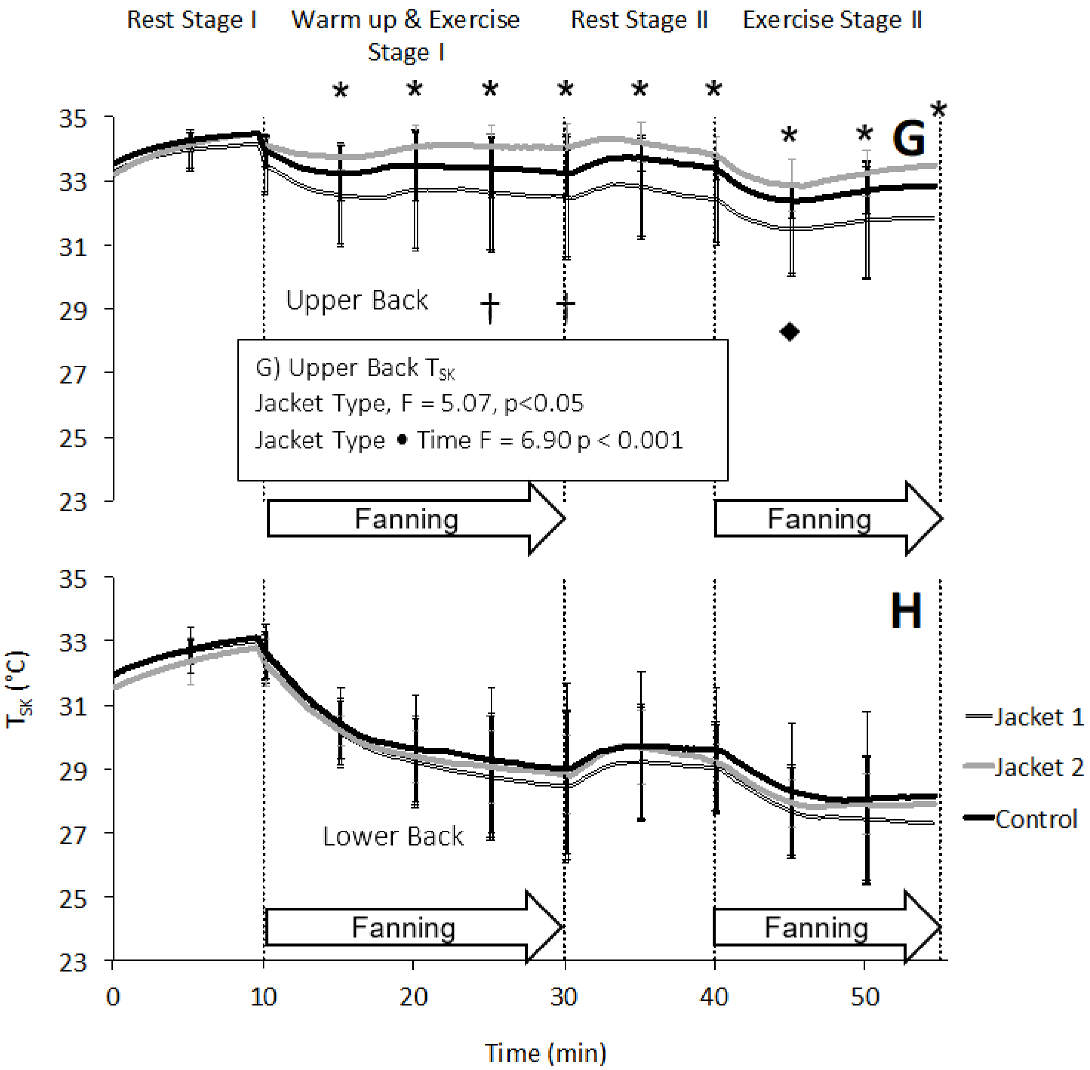


Figure 2-12 **Mean skin temperature responses of (G) upper back; (H) lower back for each Jacket Type (n=10); Jacket 1•2, * p<0.05; Jacket 1•Control, ◆ p<0.05; Jacket 2•Control, † p<0.05**

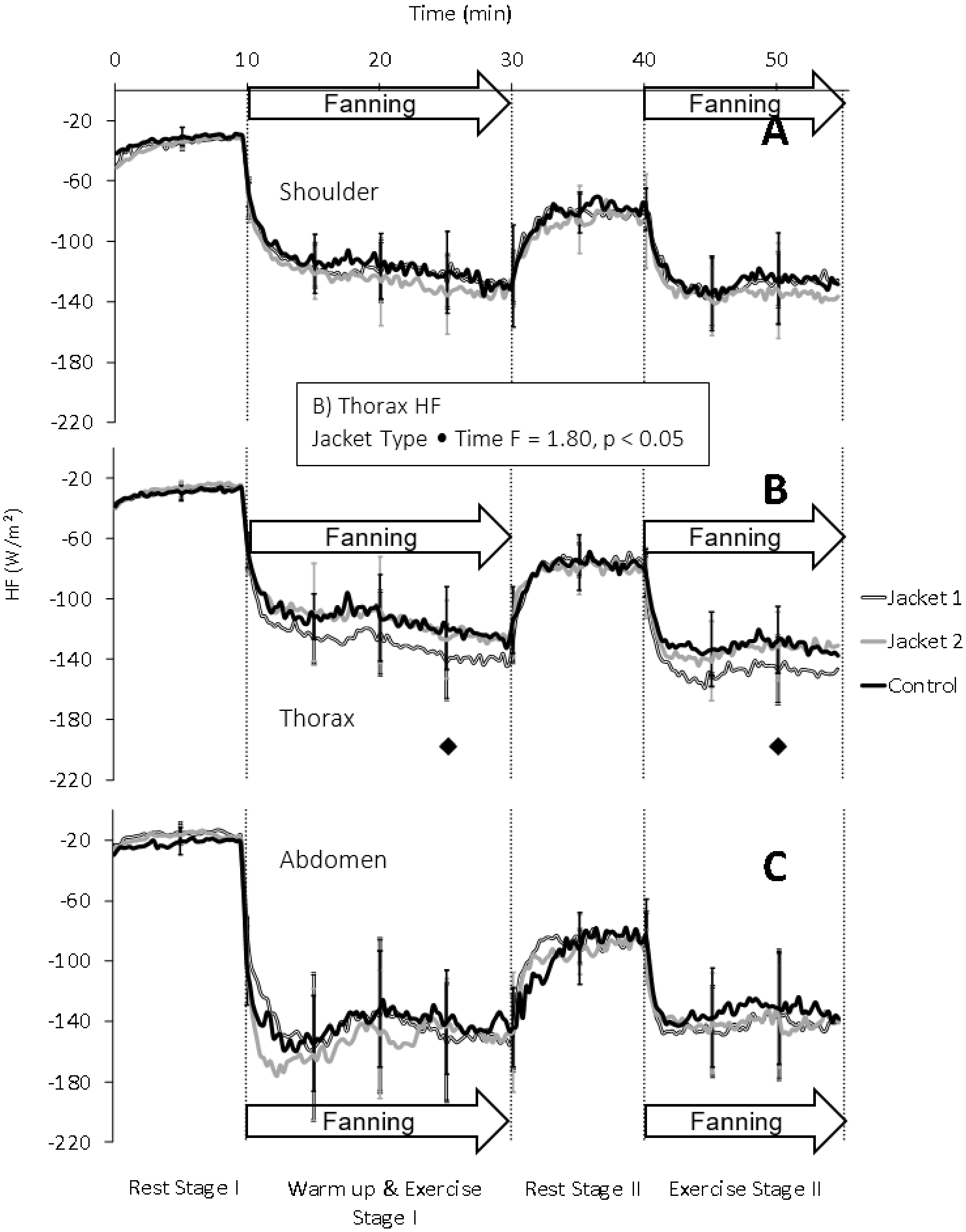


Figure 2-13 Mean heat flux responses of (A) shoulder; (B) thorax; (C) abdomen for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control, ◆ $p<0.05$; Jacket 2•Control, † $p<0.05$

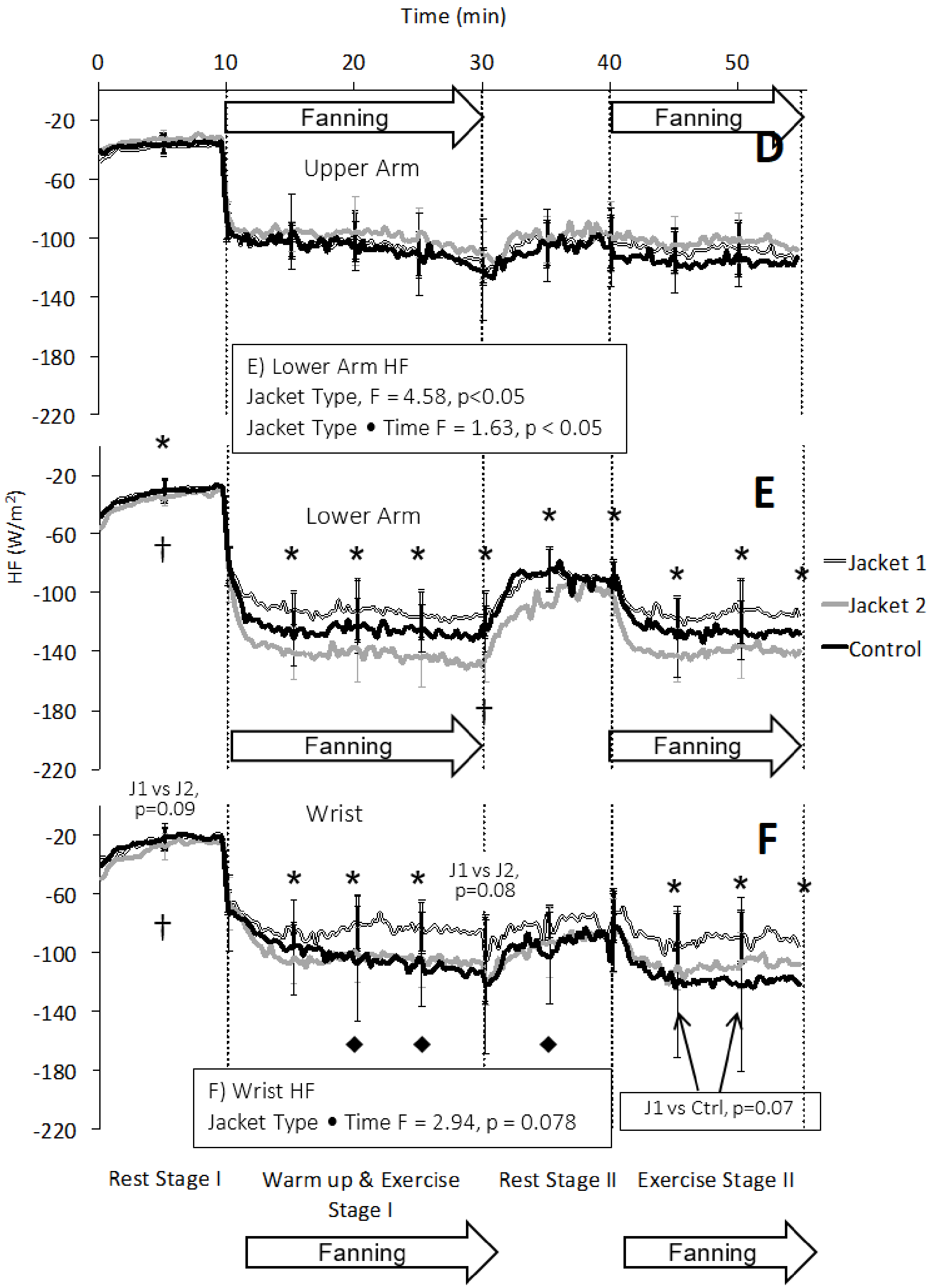


Figure 2-14 **Mean heat flux responses of (D) upper arm; (E) lower arm; (F) wrist for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control, ◆ $p<0.05$; Jacket 2•Control, † $p<0.05$**

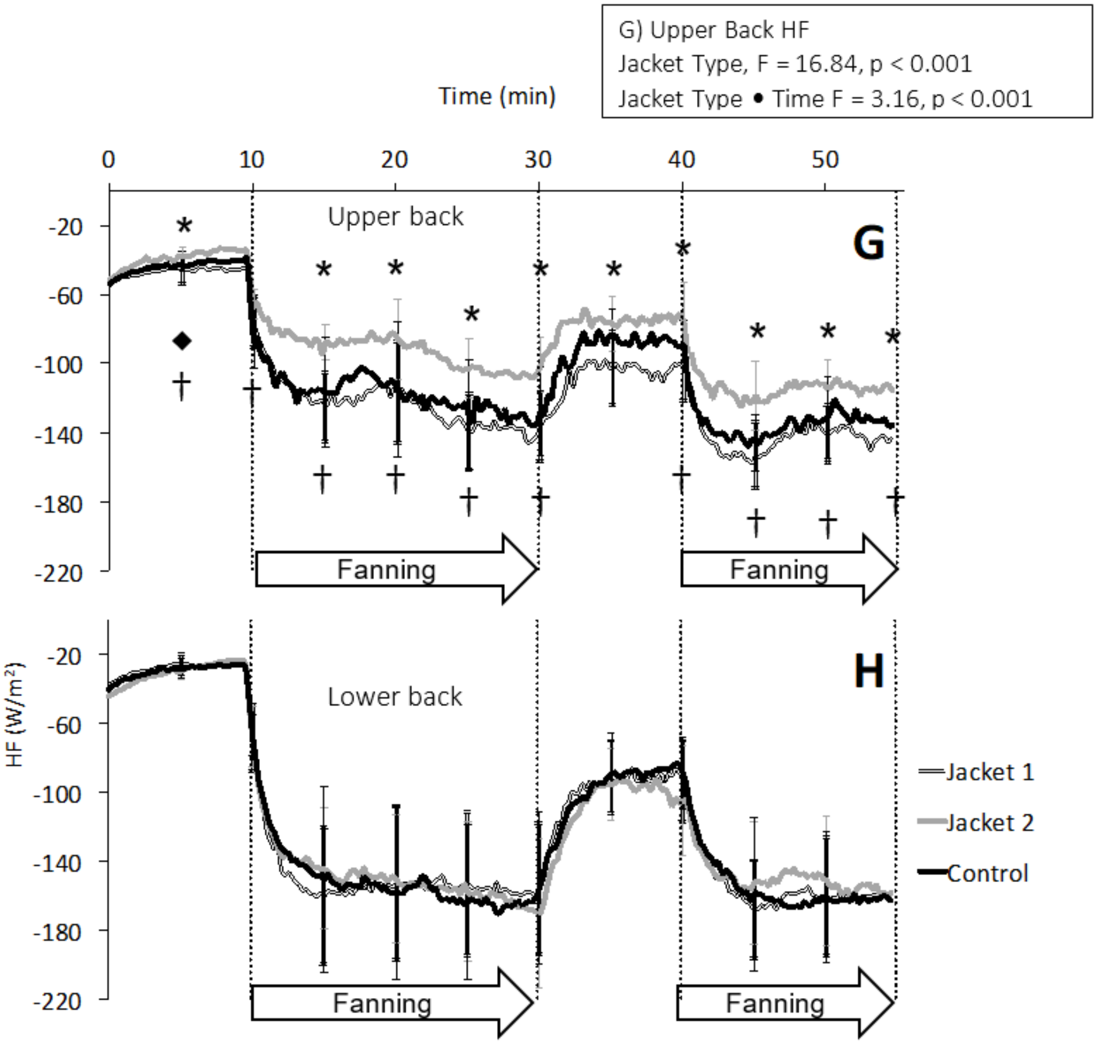


Figure 2-15 **Mean heat flux responses of (G) upper back; (H) lower back for each Jacket Type (n=10); Jacket 1•2, * p<0.05; Jacket 1•Control, ◆ p<0.05; Jacket 2•Control, † p<0.05**

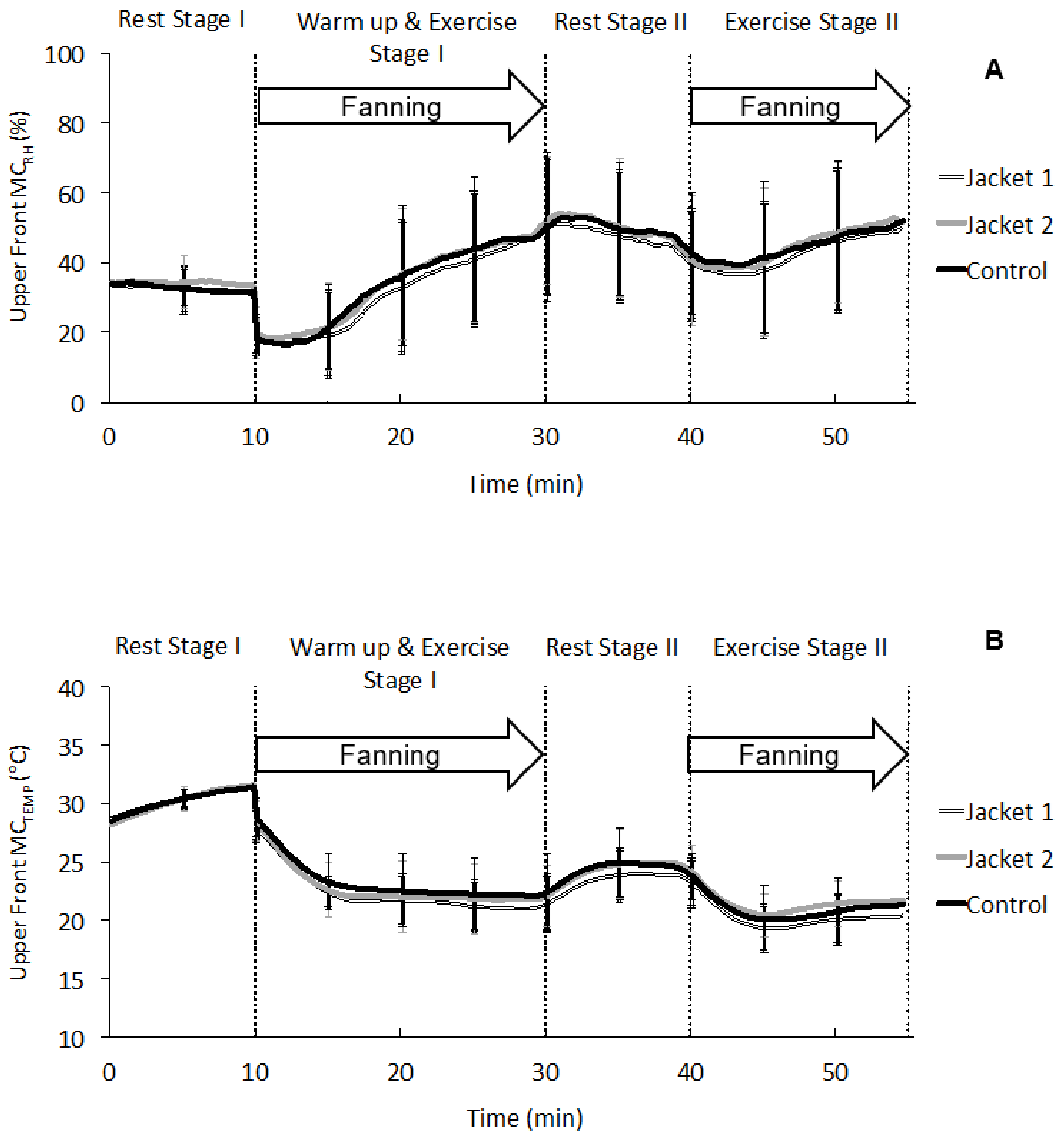


Figure 2-16 Mean Upper Front microclimate RH (MC_{RH},%) (A) and microclimate Temperature (MC_{TEMP},°C) (B) responses for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control, ◆ $p<0.05$; Jacket 2•Control, † $p<0.05$

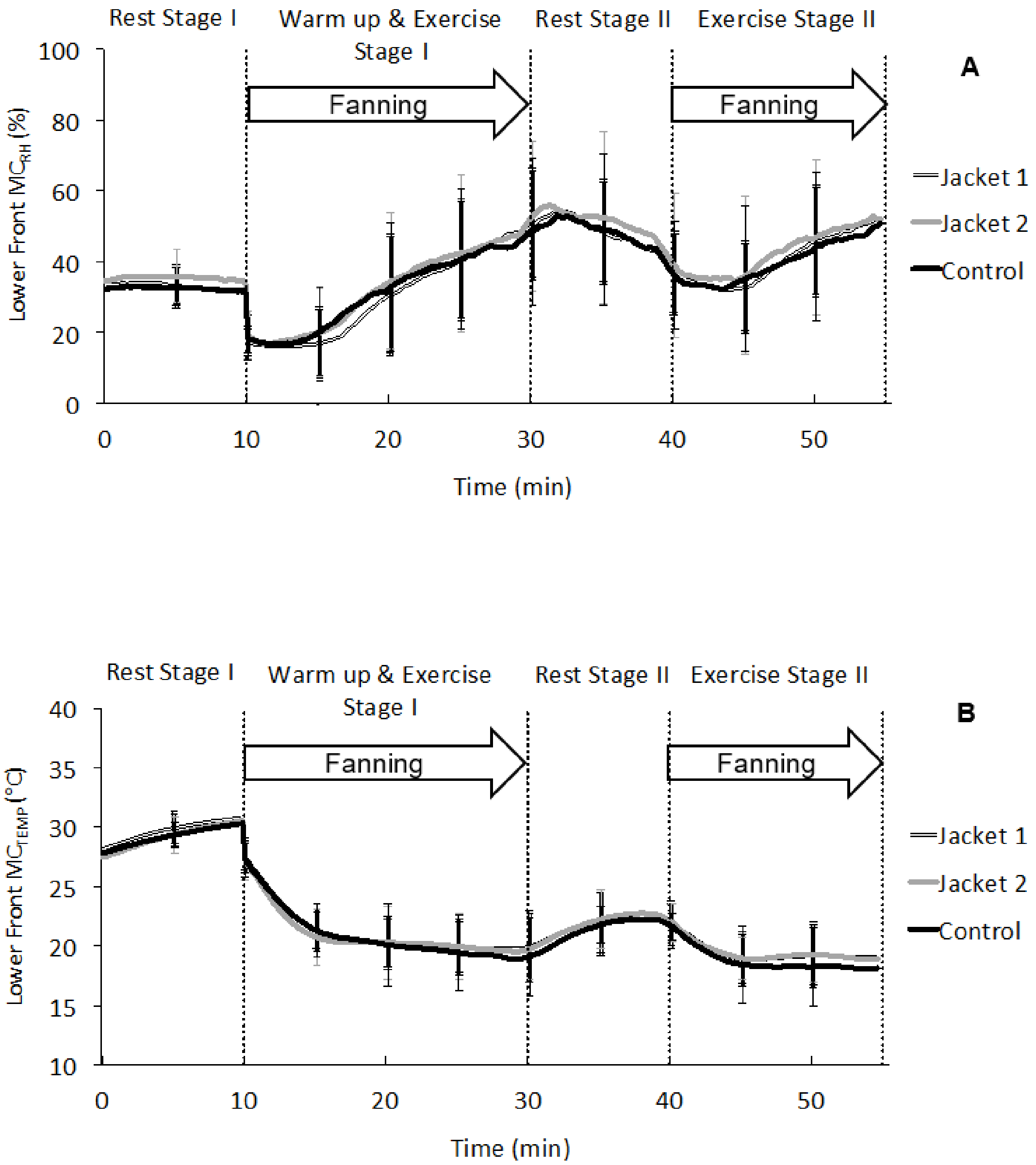


Figure 2-17 Mean Lower Front microclimate RH (MC_{RH},%) (A) and microclimate Temperature (MC_{TEMP},°C) (B) responses for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control, ◆ $p<0.05$; Jacket 2•Control, † $p<0.05$

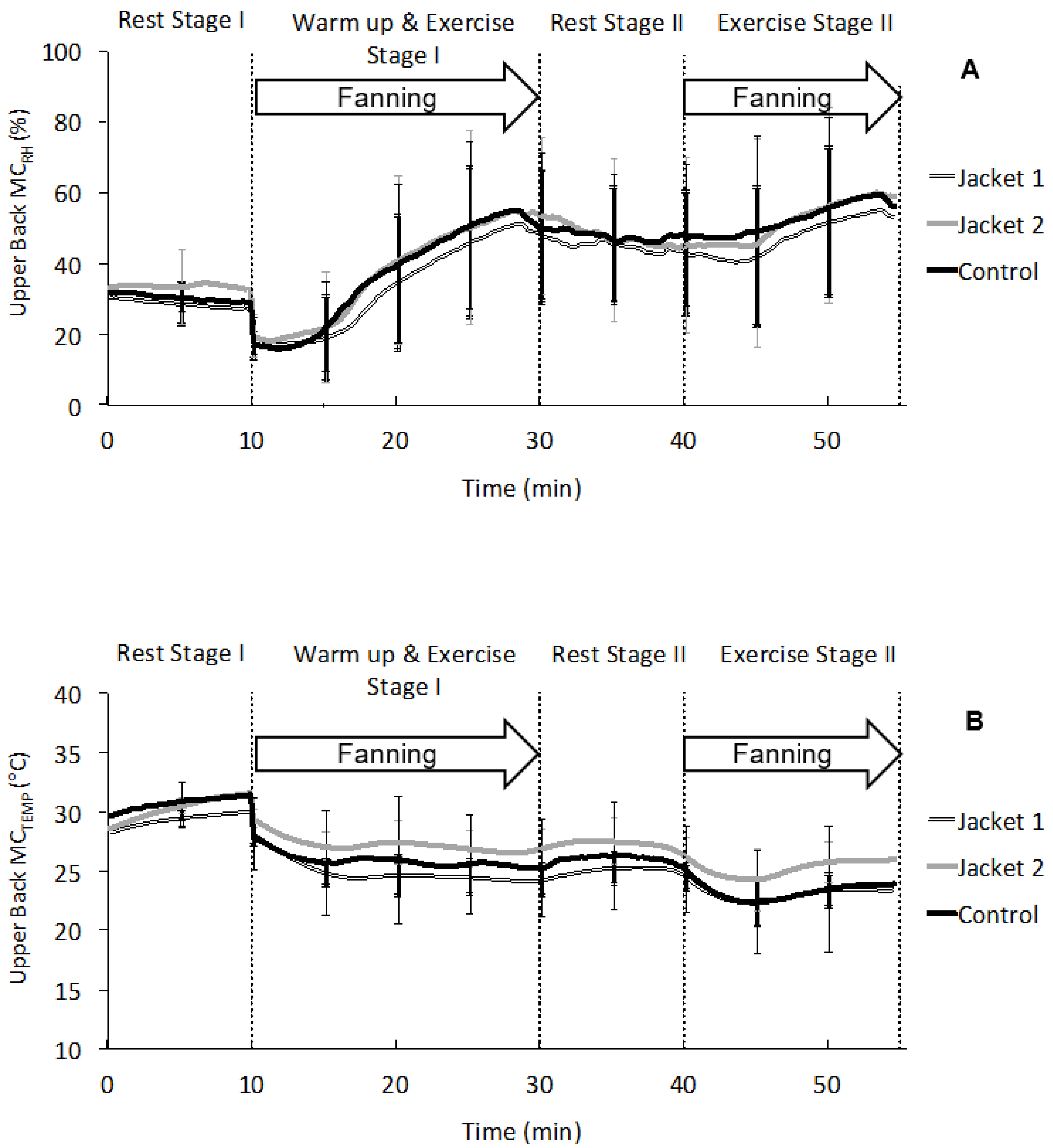
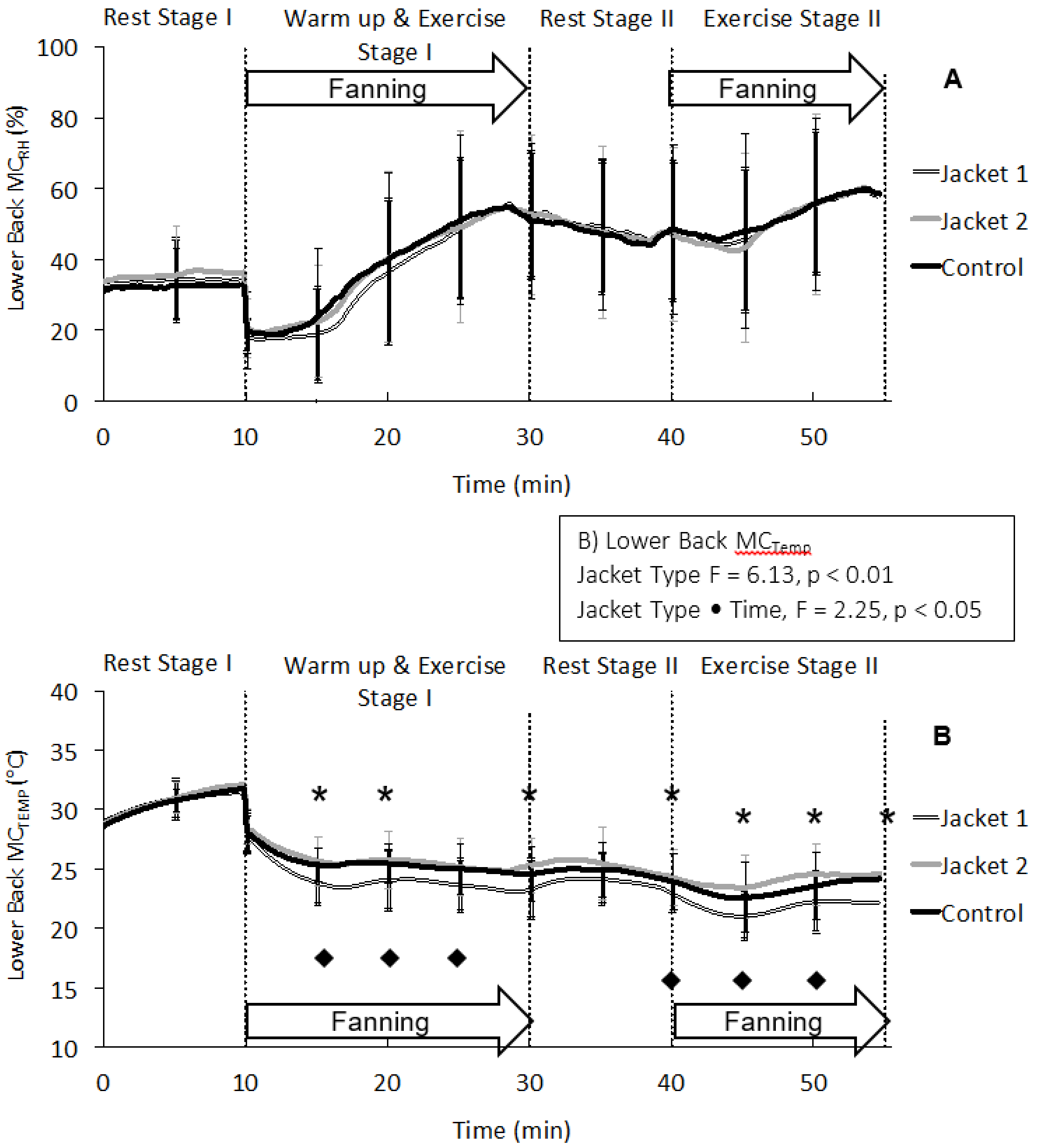


Figure 2-18 Mean Upper Back microclimate RH (MC_{RH},%) (A) and microclimate Temperature (MC_{TEMP},°C) (B) responses for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control, ◆ $p<0.05$; Jacket 2•Control, † $p<0.05$



B) Lower Back MC_{Temp}
Jacket Type F = 6.13, $p < 0.01$
Jacket Type • Time, F = 2.25, $p < 0.05$

Figure 2-19 Lower Back microclimate RH (MC_{RH},%) (A) and microclimate Temperature (MC_{TEMP},°C) (B) responses for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control, ◆ $p<0.05$; Jacket 2•Control, † $p<0.05$

Chapter 3.

Effect of Jacket Type on Thermal Comfort Votes During Rest and Exercise in the Cold

3.1. Introduction

Thermal comfort (TC) can be described as a sensation created by many factors to influence an overall satisfaction or dissatisfaction of the surrounding environment (Havenith, 2003; Holmér, 2004a). Core temperature (T_C) and skin temperature (T_{SK}) have been shown to the influence TC responses (Flouris & Schlader, 2015; Gagge et al., 1967; M. Nakamura et al., 2008; Yao et al., 2008). When testing women's winter jacket designs, influences on these T_C and T_{SK} inputs to TC need to be carefully controlled and this includes the influence of the menstrual cycle.

Due to changes in hormone concentrations of LH, estradiol and progesterone between the follicular and luteal phases of the menstrual cycle, T_{SK}, T_C and metabolic rate can change, which can ultimately affect TC (Kim & Tokura, 1995) (Israel & Schneller, 1950; Webb, 1986). Higher hormone concentrations of hormones in the luteal phase have also been suggested to cause an increased sensitivity to a cool sensation when T_{SK} exceeds 36°C (Kenshalo, 1966). Kim et al. indicated in transitions between ambient temperatures from 30˚C to 15˚C, women in the luteal phase felt cooler and more uncomfortable than the volunteers in the follicular phase (Kim & Tokura, 1995). This difference was attributed to higher metabolic rates during the luteal phase, which in turn caused an increase in skin thermal conductance (K_{SK}) (Kim & Tokura, 1995). With such variable physiological responses in the luteal phase influencing TC, in order to determine the most effective jacket design for neutral TC votes for women exercising in the cold, the best period for assessing novel winter jacket designs is in the follicular phase when T_C and T_{SK} values are more stable and thus comparable.

Exercise has been shown to influence thermal sensation in women (Gerrett et al., 2015), which can ultimately affect TC votes. Gerrett et al., showed a reduced sensitivity to a cold stimulus during exercise as compared to a resting state (Gerrett et al., 2015). Regional differences in sensitivity to a cold stimulus during rest and exercise were also evident. The upper arms were more sensitive than the lower arms and the anterior torso was more sensitive than the posterior torso, but only during rest whereas this was the opposite during exercise (Gerrett et al., 2015). Changes in regional thermal sensation to cold for women during exercise and rest are important to take into account, when designing a winter jacket of varied placement of fabric thermal resistance in order to provide the best TC.

Nakamura et al., during whole-body mild cold exposure, showed that cooling of the upper back, lower back and abdomen, at rest, all increased thermal discomfort, yet did not influence overall body TC (M. Nakamura et al., 2013). Nakamura et al's study indicates the importance of assessing regional TC, since changes in overall TC may not be observed. Also, further investigation to assess if regional TC during exercise is also independent of overall TC is warranted in order to determine the best placement of fabric thermal resistance in a jacket for women during rest and exercise in the cold. When designing a winter jacket for exercising in the cold, it is important to not only focus on whole-body TC, but also regional TC, in order to select the appropriate placement of the garment's fabric of varied thermal resistances.

The purpose of this study was to assess if the varied regional placement fabric thermal resistance in 2 women's winter jackets gave better regional as well as overall TC votes compared to a jacket of consistent fabric thermal resistance.

Hypothesis 3.1: It was hypothesized in the same cold conditions of -4°C and at the same moderate exercise intensity, that 2 jackets of similar total fabric thermal resistance that have their regional fabric thermal resistance values placed either in an inverse proportion (Jacket 1) or in a direct proportion (Jacket 2) to previously reported T_{SK}, (Fournet et al., 2013), would elicit different TC votes relative to a jacket of consistent overall thermal resistance.

Hypothesis 3.2: It was also hypothesized that Jacket 1, with its regional fabric thermal resistance placed in an inverse proportion (Jacket 1) to previously reported T_{SK} (Fournet et al., 2013), would give T_{SK} closer to 28°C and an improved overall and regional TC relative to a jacket (Jacket 2) with regional fabric thermal resistance values placed in a direct proportion to previously reported T_{SK} (Fournet et al., 2013).

3.2. Methods

3.2.1. 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 and time, without reason.

3.2.2. Participants

Each woman prior to her first trial completed a medical history form and a physical activity readiness questionnaire (PAR-Q) and signed an informed consent form. Each volunteer was also asked to provide information regarding the start date and the duration of their menstrual cycle in order to schedule each of their trials in the follicular phase of their menstrual cycle. The dates for the trials were scheduled between days 1-12 of the follicular phase of each volunteer's menstrual cycle. Each volunteer completed a $\dot{V}O_{2PEAK}$ test, DEXA scan, 4 whole body scans and 3 cold chamber trials. To estimate the sample size needed for the study a power calculation was performed for whole body thermal comfort (TC). Table 3-1 gives the sample size justification for the outcome variables and Table 2-2 provides the volunteer characteristics.

Each volunteer was recruited to fit a medium clothing size and during the orientation all volunteers had the opportunity to make sure the clothing fit properly.

The women in this study had a mean age (± SD) of 33.9 (5.7), mean height of 1.65 m (0.08), a mean weight of 57.1 kg (6.2). Six of the women were in follicular phase of the menstrual cycle and the remaining 4 had amenorrhea.

3.2.3. Instrumentation

$\dot{V}O2_{PEAK}$ Test

Each volunteer wore a facemask connected to a flow sensor to assess their ventilation and from which expired gases where drawn and analyzed with a breath-by-breath metabolic cart (COSMED USA Inc., Chicago, USA). Prior to each trial the flow sensor was calibrated for volume using a 3 L syringe and two gas tanks one with 16%

O_2, 5% CO_2, and 79% N_2 and the other with 26% O_2, balance N_2 were used to calibrate the gas sensors of the metabolic cart. All of these calibrations were performed at room temperature of ~ 22°C and relative humidity of ~40%. Heart rate was recorded using a Polar HR monitor (Polar Electro V800, Kempele, Finland) and thorax strap and core temperature was collected by a pill (T_{PILL}) ingested 3 hours prior to the test (VitalSense, Bend, USA).

Climate Chamber Trials

All jacket trials took place in a climatic chamber (643399-00D, Weiss Envirotronics Inc, Santa Clara, USA). Heart rate was recorded using a Polar HR monitor (Polar Electro V800, Kempele, Finland) and thorax strap. Mass was measured using a scale (Seca 515/514, Hamburg, Germany) before and after each chamber trial. Height was measured before the first trial using an electronic stadiometer (Seca stadiometer 264, Hamburg, Germany).

Thermal Comfort

Thermal Comfort (TC) was assessed at the following min 5, 10, 15, 18, 22, 26, 28, 30, 32, 36, 38, 40, 42, 46, 50, and 54 throughout the trial using a modified IREQ (required clothing insulation method) thermal comfort scale from Holmér (2004). On the scale -4 represented very, very cold and +4 represented very, very hot (Figure 3.4). Overall TC votes were assessed as well as regional TC for Thorax, Abdomen, Upper Arm, Lower Arm, Upper Back and Lower Back as seen in Figures 3.1-3.3.

Technical Apparel

Each volunteer wore the same base layer in each cold trial that included a long sleeve top, tights, socks, sports bra and underwear in the preferred sizes (Table 2-3). Three jackets employed in the study included Jacket 1 with regional fabric thermal resistance values placed in an inverse proportion previously reported T_{SK} (Fournet et al., 2013) (Figure 3-1), Jacket 2 with regional fabric thermal resistance values placed in a direct proportion to previously reported T_{SK} (Fournet et al., 2013) (Figure 3-2), and a Control Jacket of consistent fabric thermal resistance T_{SK} (Figure 3-3) were used in the study. The regional pattern of fabric thermal resistance for the three coats was varied for Jackets 1 and 2, but constant for the control jacket. The conductive/convective resistance for the base layer clothing can be seen in Table 2-3A. The conductive/convective and evaporative resistances for each of the 3 jackets as well as the calculation for the $R_{CT\ TOTAL}$ for each jacket is given in Table 2-3B. The jackets were not washed in order to prevent any changes to the thermal resistance values.

3.2.4. Data Acquisition

The $\dot{V}O2_{PEAK}$ test was performed on a treadmill while collected expired gases with a breath-by-breath metabolic cart (COSMED USA Inc., Chicago, USA). Heart rate was recorded by telemetry using a Polar HR monitor and thorax strap (Polar Electro V800, Kempele, Finland).

Thermal comfort votes were recorded by hand on a data sheet approximately every 2-4 minutes during the rest and exercise stages. All the hand recorded data sheets were then transferred to a spreadsheet on a computer.

3.2.5. Protocol

$\dot{V}O2_{PEAK}$ *Test*

Each volunteer performed an incremental exercise test from rest to the point of exhaustion on treadmill to determine $\dot{V}O2_{PEAK}$. Upon arrival the volunteer read and signed an informed consent. The volunteer's height and weight was then measured. An 8-10 min warm up on the treadmill was executed prior to the $\dot{V}O2_{PEAK}$ test. The protocol for the test increased speed by 1 km/h starting at 6 km/h until reaching 11 km/h on the treadmill. Once the speed had been reach, the grade of the treadmill will increase by 2% each minute. Termination of the test occurred once the volunteer reached a steady age-predicted maximal HR, a respiratory exchange ratio (RER) of 1.15 unitless, or a plateau in volume of consumed oxygen ($\dot{V}O2$). Due to the nature of a maximal test, the volunteers were made aware of symptoms to be expected and informed, if necessary, the test could be terminated prior to reaching $\dot{V}O2_{PEAK}$. A harness was worn throughout the duration of the test as a safety precaution.

Cold Climatic Chamber Trials

The performance of each jacket and the TC ratings was assessed during three separate 55 min sessions (Table 3-2) at an exercise intensity 10% below their pre-determined ventilatory threshold and the corresponding HR; the method for determining these thresholds is given below in the Statistical Analyses section. On three separate days, three trials were conducted in the climatic chamber at a dry bulb temperature of -4°C with a RH of 50% to test the three jacket designs. During the running stages, but not at rest, a fan set at a velocity of ~1.7 m/s was used to simulate running conditions. The volunteers were showed a body map of the regions they were being asked to rate before each trial. During each trial when the volunteer was asked to rate TC, the tester pointed to the region of the body being rated in order to provide visual guidance to the volunteer where to rate their TC as well as for consistency between the volunteers.

3.2.6. Statistical Analysis

The TC votes were analyzed using a 2-way repeated measures ANOVA with factors of Jacket Type (1, 2 and Control) and Environmental Stage (Rest Stage I, Warm up and Exercise Stage I, Rest Stage II, Exercise Stage II).

The ventilatory threshold from the $\dot{V}O_{2PEAK}$ test for each volunteer was determined using Vieth's method (Vieth, 1985). Ventilatory equivalent for oxygen ($V_E/\dot{V}O_2$) was plotted as a function of the volume of consumed oxygen ($\dot{V}O_2$) from the incremental $\dot{V}O_{2PEAK}$ test. This is an iterative method that fits two linear regression functions to the data to estimate where the first regression line intersects with the second regression line; the threshold is at the point with a minimized residual sum of squares for the 2 regression lines.

During the trials the intensity at which each volunteer exercised was the HR at 10% below the value corresponding to the ventilatory threshold. The Vieth threshold detection method was calculated with code written in LabVIEW (Ver. 7.1, National Instruments, Austin, TX, USA). Results were considered statistically significance if $p<0.05$.

3.3. Results

There was a significant interaction ($p=0.01$) between Jacket Type and Time ($p<0.05$) for Overall TC Vote (Fig. 3-5). During Exercise Stage I and at the start of the Rest Stage II, Jacket 1 gave TC ratings significantly closer ($p<0.05$) to thermoneutral than both the Control Jacket and Jacket 2.

No effect of Jacket Type was evident for regional TC for the Thorax (Figure 3-6) nor on the Abdomen (Figure 3-7). For Upper Arm TC (Figure 3-8) and Lower Arm TC (Figure 3-9) there were trends ($0.077 < p < 0.094$) for a Jacket Type by Time interaction. For the Upper Arm ($0.01 < p < 0.07$) and for the Lower Arm ($0.02 < p < 0.06$) Jacket 1 gave TC votes less than Jacket 2 during Exercise Phase I and during the rest in the cold chamber.

There was a trend ($p=0.06$) for significant main effect of Jacket Type for the Upper Back TC (Figure 3-10). There were significant interactions ($p<0.05$) for Jacket Type and Time for TC for the Upper Back (Figure 3-10; $p < 0.001$) and Lower Back (Figure 3-11; $p=0.021$). This main effect and interaction for Upper Back TC votes between Jacket 1 and 2 was explained by significant differences ($p < 0.05$) during the entire period in the climatic chamber, where Jacket 1 received TC votes closer to thermoneutral than both Jacket 2 and the Control Jacket. The significant Jacket Type and Time interaction for the Lower Back TC votes was explained by TC votes that were closer to thermoneutral for Jacket 1 as compared to Control during Exercise Stage I, the beginning of Rest Stage II and the mid point of Exercise Stage II.

3.4. Discussion

The main novel finding in the study was overall thermal comfort (TC), where TC was best for Jacket 1 during the first 20 min of exercise in the climatic chamber but subsequently for overall TC, at rest or in Exercise Stage II, there was not a clear delineation of thermal comfort responses between the 3 jacket designs. The result supports varying regional fabric thermal resistance values in a winter coat can improve TC in women exercising submaximally in the cold but these results were most evident early on in the first exercise stage.

The second main finding in the study is reflected by the novel jacket designs influences on regional TC responses, as given in the next sections.

3.4.1. Regional Thermal Comfort Responses

The result supports varying regional fabric thermal resistance placement in a winter coat can transiently improve TC in women exercising submaximally in the cold.

Holmér's IREQ scale (Holmér, 2004a) supports that thermoneutral TC votes will be given when skin temperatures are closer to 28°C. As such, in the site by site analysis for regional TC votes, an assessment was made for which jackets at a given measurement site gave the best TC votes and if on the surface of the body the T_{SK} values were closer to 28°C for a better TC vote.

(a) Shoulder, Upper Arm and Lower Back Thermal Comfort Responses

Since the Upper Arm and Lower Back T_{SK} responses were mostly the same (Figures 2-7 and 2-8), this suggests the TC votes at or close to these 2 sites would also be the same. Thermal Comfort was assessed on the Upper Arm and Lower Back (Figures 3-8 and 3-11) where women in Jacket 1 gave TC votes closer to thermoneutral than Jacket 2 or the Control Jacket in Exercise Stage I. The results for these locations do not support T_{SK} as the principal input determining these TC responses.

(b) Thorax and Upper Back Thermal Comfort Responses:

For the Thorax and Upper Back the T_{SK} values (Figures 2-10 B and 2-12 G) closer to 28°C for Jacket 1 support that better TC votes would be given for Jacket 1 relative to Jacket 2 (Figures 3-6 and 3-10). The TC results do not appear to follow the physiology for the Thorax as no differences were evident in TC votes between any of the Jackets at that site. For the Upper Back, however, showed TC votes were significantly lower for Jacket 1 relative to Jacket 2 supporting that T_{SK} values In Jacket 1 closer to 28°C give better thermal comfort.

(c) Abdomen and Lower Arm Thermal Comfort Responses

As might be expected from the similar T_{SK} values, Abdomen TC votes were not significantly different between the jackets. For the Lower Arm, Jacket 1 relative to Jacket 2 gave TC votes closer to a thermoneutral vote of 0 in Exercise Stage I. This again does not follow the physiology, as no T_{SK} differences were evident for the Lower Arm, or for the Wrist, between the 3 jacket designs.

The Chapter 2 results support the hypothesis that when varying regional fabric thermal resistance in a winter jacket can in some locations perform differently physiologically than a jacket with consistent thermal fabric resistance. These physiological changes, however, do not always mirror TC changes. When the results are considered it is clear in Exercise Stage I that Jacket 1 gave the best TC votes of the 3 jackets tested in the study.

There is limited research on varied placement of insulation in a garment for TC responses (Nielsen & Nielsen, 1984). Studies of similar jacket designs as those in this study were not uncovered in an exhaustive literature review. Regional differences were evident in the current study's results, supporting the importance of regional body mapping in clothing physiology. These differences detected in regional thermal comfort are supported by another cold exposure study (Nakamura et al., 2013). During whole-body mild cold exposure, Nakamura (Nakamura et al., 2013) reported no effect on whole body TC, but a significant regional feeling of discomfort when locally cooling the abdomen and lower back supporting the importance of assessing regional TC since this may not influence overall TC. No observed differences for TC were apparent at the thorax and abdomen between all 3 jackets. As mentioned in Chapter 2 in this thesis, the use of the fan may have disturbed the layer of still air within the garment as well as compressed the fabric. As suggested by Havenith, wind can reduce the thickness of insulation and affect the thermal properties of a garment (Havenith, 2003). The present results support this view due to no differences between jacket designs detected on the front torso in direct line of the fan.

3.4.2. Suggested Mechanism(s)

Mechanisms of the observed differences or lack of observed differences in regional TC, may be due to reduced thermal sensitivity in women during exercise as compared to rest (Gerrett et al., 2015). Results from the current study had 2 out of the 6 sites for TC show no differences between the jackets for both exercise and rest stages. Gerrett et al., found significant differences in women's thermal sensitivity from a cold stimulus on the lateral chest as well as the medial and lateral abdomen from rest to exercise (Gerrett et al., 2015), whereas a difference in those regions was not detected currently when comparing the 3 jacket designs. These differences most likely exist since Gerrett et al., placed the cold stimulus directly on the skin, whereas the current study included the covering of a jacket. The abdomen has been previously reported to have lower T_{SK} in the cold, and is considered a very thermal sensitive area (Gerrett et al., 2014; Ouzzahra, 2012). Cold receptors in the abdomen sit closer to the skin's surface (Hensel, Andres, & von Düring, 1974) with greater density than warm receptors (Hensel, 1981), but no differences in TC were present for the Abdomen between the 3 jackets during rest or exercise. Perhaps this is due to exercise-induced analgesia (Koltyn, 2000), where stress hormones, such as adrenocorticotropic hormone and β-endorphins, are released during exercise that may limit afferent sensitivity signals being sent to the brain (Kemppainen, Pertovaara, Huopaniemi, Johansson, & Karonen, 1985), potentially influencing TC. Interestingly, the upper back had a large significant difference between jacket types. Smith & Havenith found sweat rates to be greater during exercise on the upper back as compared to the abdomen (C. J. Smith & Havenith, 2011). Although sweat rates were not measured between the three jacket types, the Upper Back for Jacket 1 contained less fabric thermal resistance, which, relative to the other two jackets, corresponded with lower T_{SK} and TC ratings closer to neutral. This could be due to the fabric with the lowest R_{CT} value that was placed over the Upper Back in Jacket 1 versus both Jacket 2 and the Control Jacket, where there is a greater sweat rate (Smith & Havenith, 2011), therefore allowing more evaporative heat loss and reduced sweat accumulation which effects thermal comfort (Fan, 2008).

Limitations for this study are similar to those discussed in Chapter 2. For future direction it may be of interest to employ a thermal sensitivity scale combined with a TC scale to allow for further interpretation of the TC votes.

3.4.3. Conclusion

Hypothesis 3.1: It was hypothesized in the same cold conditions of -4°C and at the same moderate exercise intensity, that 2 jackets of similar total fabric thermal resistance that have their regional fabric thermal resistance values placed either in an inverse proportion (Jacket 1) or in a direct proportion (Jacket 2) to previously reported T_{SK}, (Fournet et al., 2013), would elicit different TC votes relative to a jacket of consistent overall thermal resistance.

Response to Hypothesis 3.1: The evidence support that Jackets 1 and 2 with varied thermal resistance fabric over previously reported differing surface T_{SK} showed differing thermal comfort votes compared to the control Jacket with consistent overall of thermal resistance.

Hypothesis 3.2: It was also hypothesized that Jacket 1, with regional fabric thermal resistance placed in an inverse proportion to previously reported T_{SK} (Fournet et al., 2013), would give T_{SK} closer to 28°C and an improved overall and regional TC relative to a jacket (Jacket 2) with regional fabric thermal resistance values placed in a direct proportion to previously reported areas of T_{SK} (Fournet et al., 2013).

Response to Hypothesis 3.2: The hypothesis is partially accepted as the evidence supports that in the cold, Jacket 1 during the first 15 min of exercise gave improved overall and regional TC votes relative Jacket 2 but the effects of the differing jacket designs were not as evident in Rest Stage II and in Exercise Stage II.

3.5. Tables

Table 3-1 Sample size justification for thermal comfort variable with a power of 80% and an α-level set at 0.05

Outcome Variable	Difference in Mean Worth Detecting	Standard Deviation	Number of Participants
Overall Thermal Comfort (unitless)	1	0.75	7

Table 3-2 Trial Stages

Stage	Rest Stage I	Warm-up Stage	Exercise Stage I	Rest Stage II	Exercise Stage II
Duration (min)	10	5	15	10	15
T_{DB} (°C)	~22	- 4	- 4	- 4	-4
Posture	Seated	Submax. Running	Submax. Running	Standing	Submax. Running
TC Vote Times (min)	5, 10	-	15, 18, 22, 26, 28	30, 32, 36, 38	40, 42, 46, 50, 54

3.6. Figures

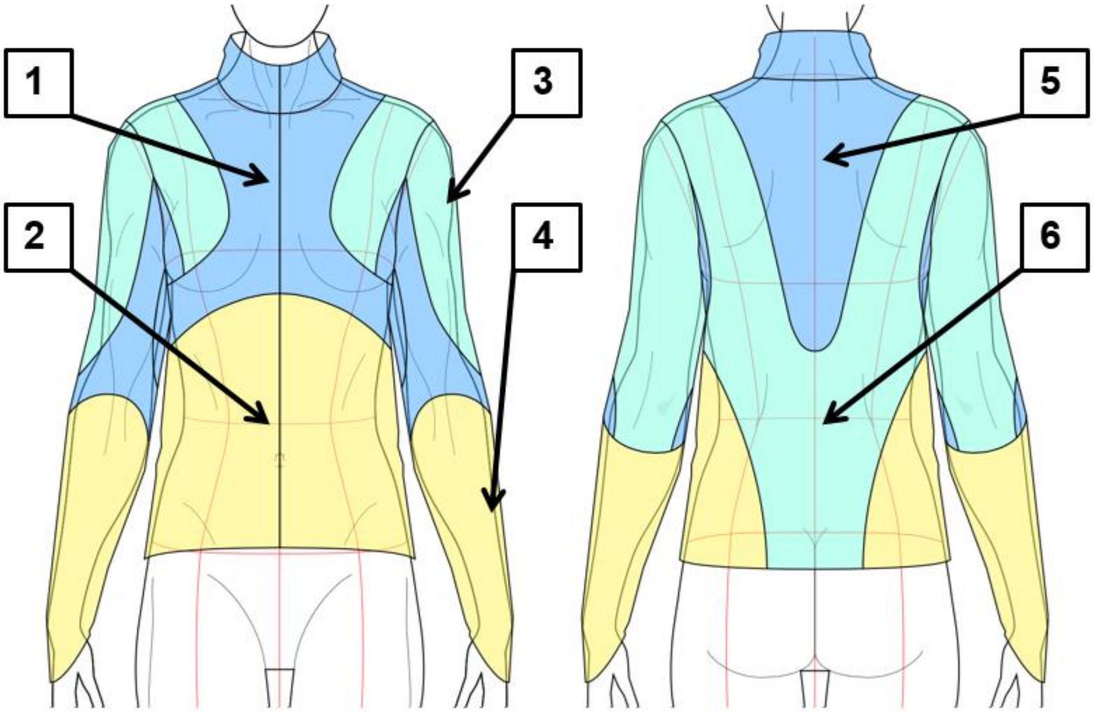


Figure 3-1 Locations of regional TC votes asked during the Jacket 1 trials

(1) Thorax, (2) Abdomen, (3) Upper Arm, (4) Lower Arm, (5) Upper Back and (6) Lower Back

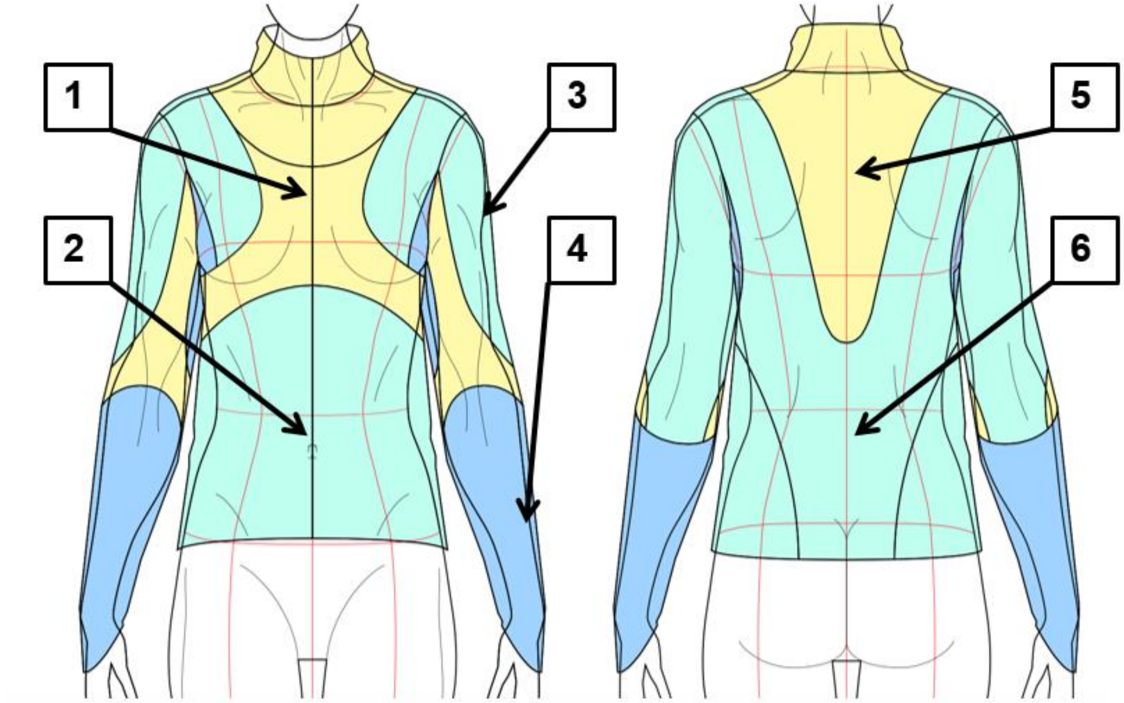


Figure 3-2 Locations of regional TC votes asked during the Jacket 2 trials

(1) Thorax, (2) Abdomen, (3) Upper Arm, (4) Lower Arm, (5) Upper Back and (6) Lower Back

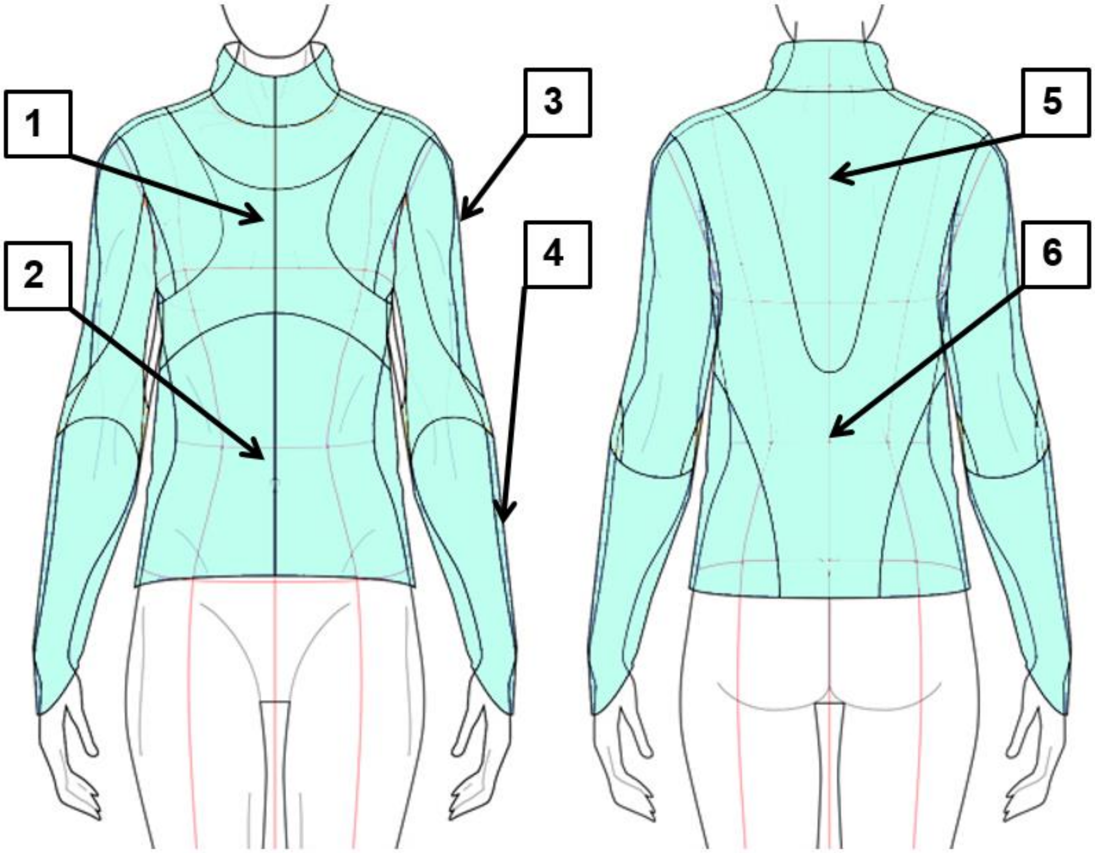


Figure 3-3 Locations of regional TC votes asked during the Control Jacket trials

(1) Thorax, (2) Abdomen, (3) Upper Arm, (4) Lower Arm, (5) Upper Back and (6) Lower Back

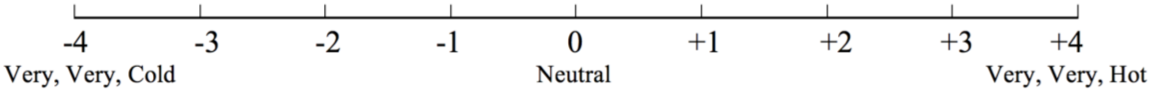


Figure 3-4 **Modified required clothing insulation method (IREQ) thermal comfort scale from Holmér (2004): -4 represents very, very cold and +4 represents very, very hot.**

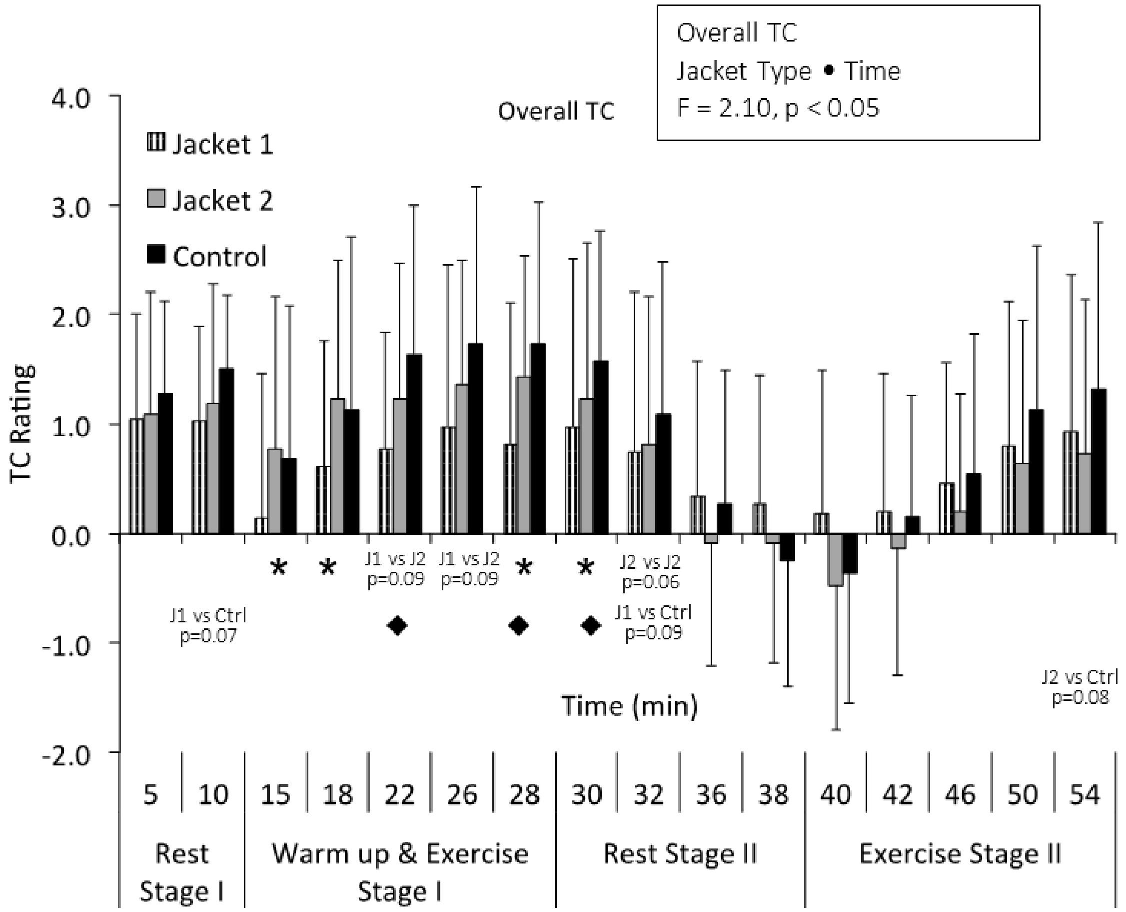


Figure 3-5 Mean Overall Thermal Comfort (TC) votes for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control, ◆$p<0.05$; Jacket 2•Control, † $p<0.05$

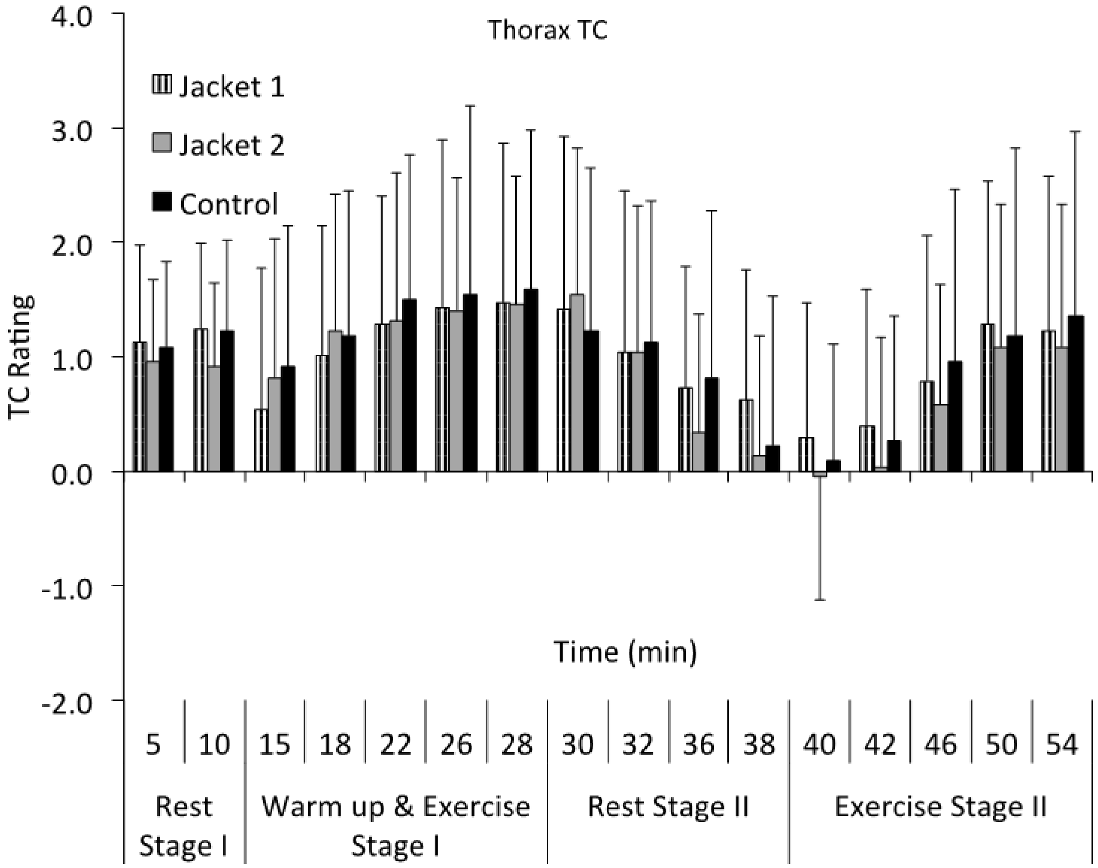


Figure 3-6 Thorax Thermal Comfort (TC) votes for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket1•Control,◆$p<0.05$; Jacket 2•Control, † $p<0.05$

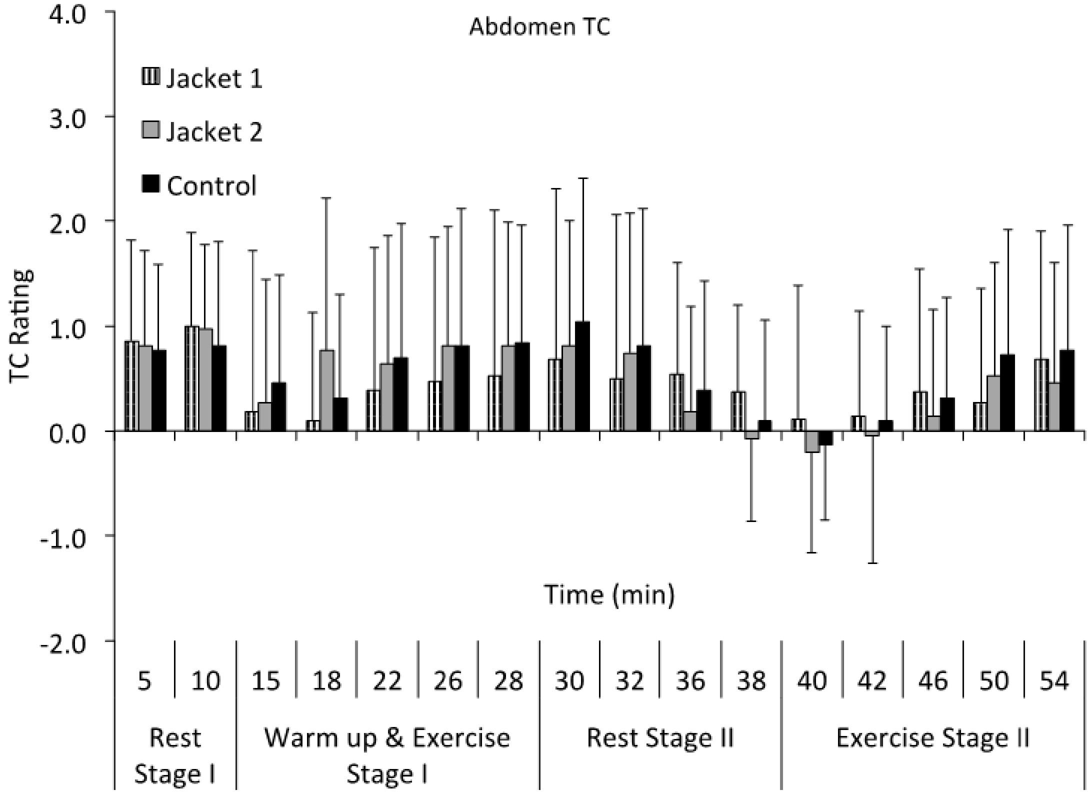


Figure 3-7 **Abdomen Thermal Comfort (TC) votes for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$;Jacket 1•Control,◆ $p<0.05$; Jacket 2•Control, † $p<0.05$**

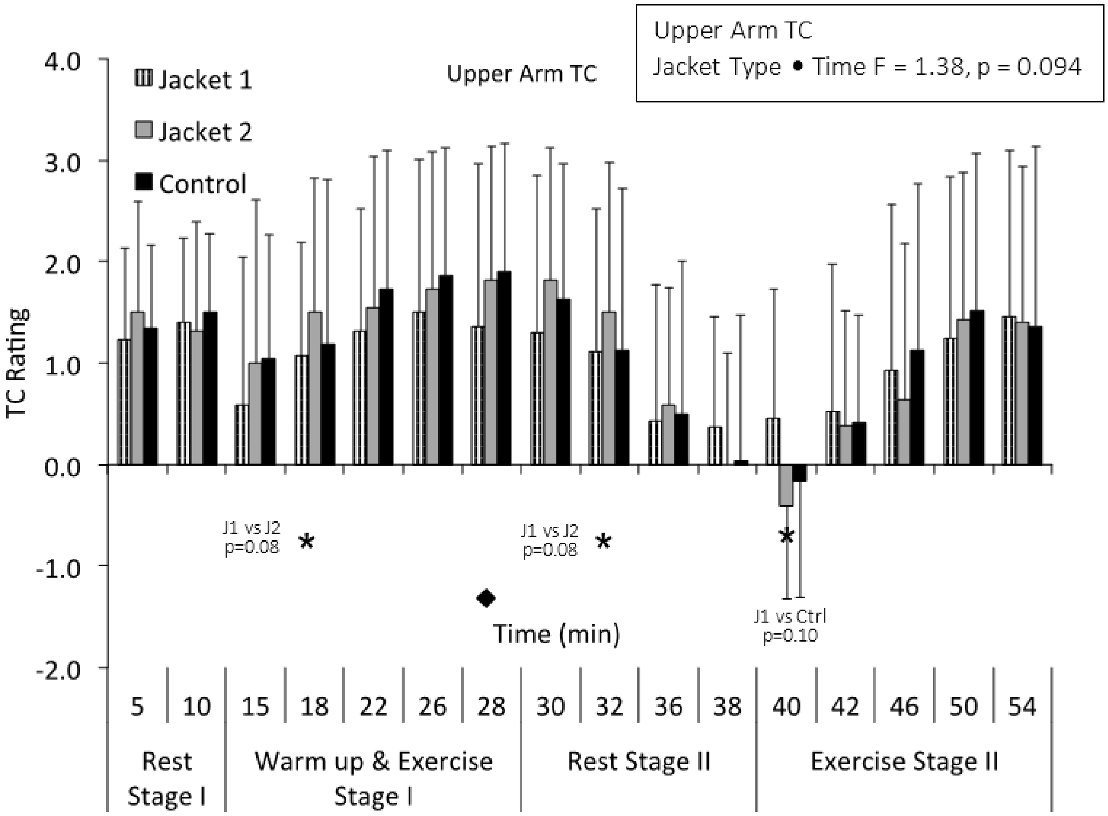


Figure 3-8 Upper Arm Thermal Comfort (TC) votes for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control,◆ $p<0.05$; Jacket 2•Control, † $p<0.05$

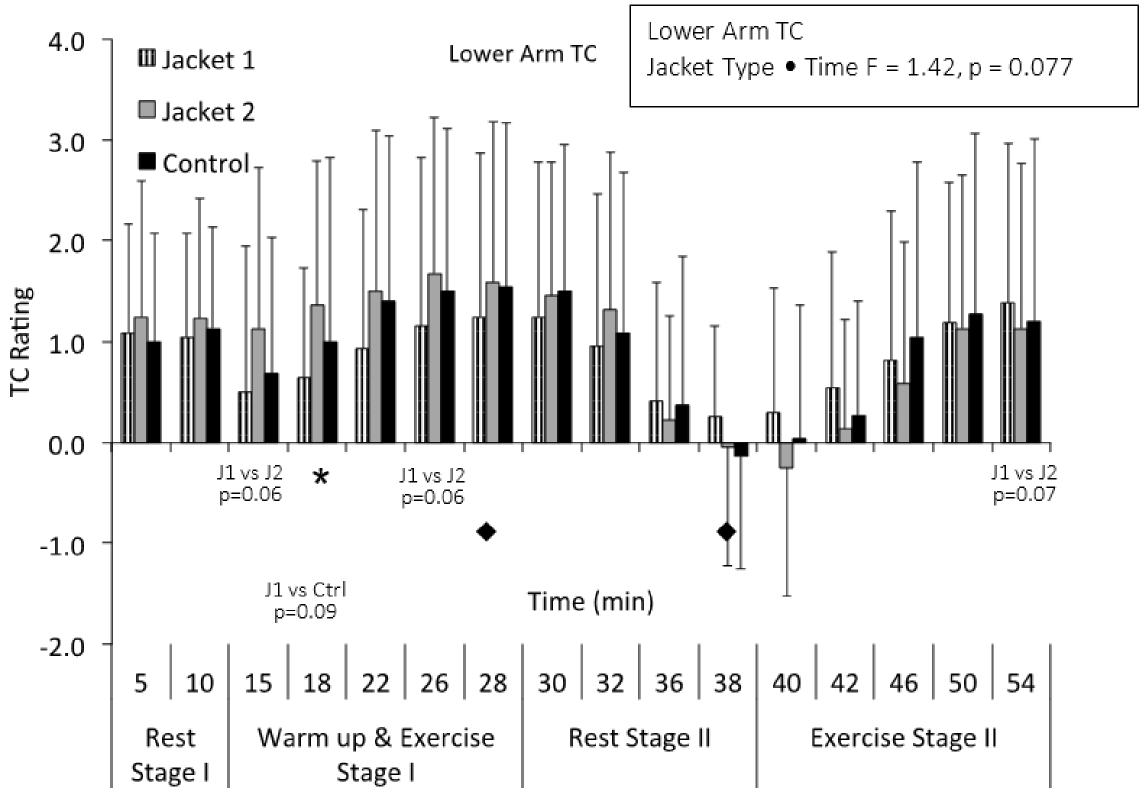


Figure 3-9 Lower Arm Thermal Comfort (TC) votes for each Jacket Type (n=11); Jacket 1•2, * $p<0.05$; Jacket 1•Control, ◆ $p<0.05$; Jacket 2•Control, † $p<0.05$

Upper Back TC
Jacket Type, F = 3.40, $p = 0.06$
Jacket Type • Time F = 2.32, $p < 0.001$

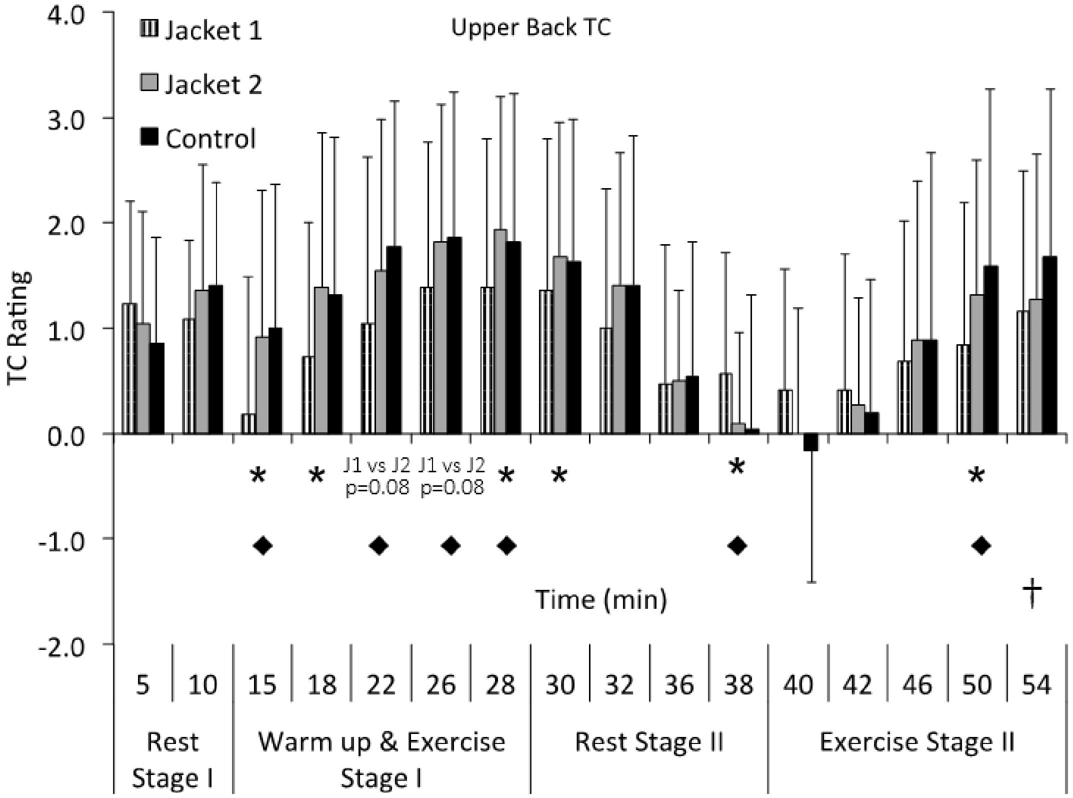


Figure 3-10 Upper Back Thermal Comfort (TC) votes for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control,◆ $p<0.05$; Jacket 2•Control, † $p<0.05$

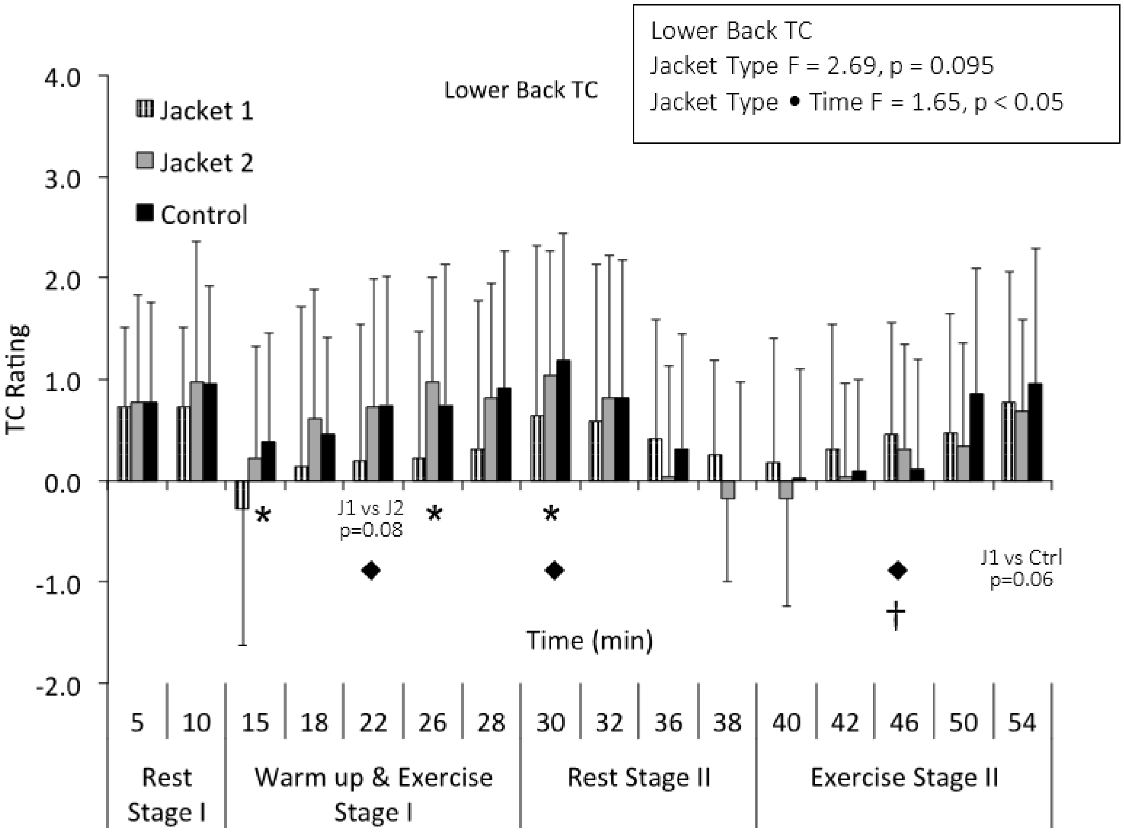


Figure 3-11 Lower Back Thermal Comfort (TC) votes for each Jacket Type (n=10); Jacket 1•2, * $p<0.05$; Jacket 1•Control,◆ $p<0.05$; Jacket 2•Control, † $p<0.05$

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