Regional thermal sensitivity
to cold at rest and during exercise

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Regional thermal sensitivity to cold at rest and during exercise

by

Yacine Ouzzahra

A Doctoral Thesis submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

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ABSTRACT

Thermal sensitivity has been of scientific interest for almost a century. Despite this, several research questions within this field remain unanswered, particularly regarding the specific distribution of thermal sensitivity to cold across the human body. Additionally, while exercise is known to cause a cold stimulus to be perceived as less unpleasant according to the principle of thermal alliesthesia, less has been reported on the effects of exercise on thermal sensitivity to cold. With applications mainly related to clothing insulation and design in mind, the present research project aimed to investigate thermal sensitivity to cold at whole body segments, as well as within body segments, at rest and during exercise. Additionally, a comparison of thermal sensitivity to cold between genders and between ethnic groups was also performed.

In study 1, the effects of whole body segments cooling was investigated at rest and during exercise. A customised high density water perfused suit (WPS) was used to manipulate skin temperature ($T_{sk}$). The data revealed technical limitations related to the protocol as well as the uniformity of the WPS in terms of both contact and tubing density.

Study 2 aimed to explore the research questions posed in study 1, while addressing the limitations highlighted. For this purpose, the testing protocol was substantially changed, and improvements were made to the WPS. Individual body segments were continuously cooled during consecutive periods of rest, exercise and recovery. Results showed significant differences in thermal sensitivity to cold between body segments. Regarding the effects of condition, the results revealed a significant decrease in thermal sensitivity to cold during exercise and post-exercise recovery, compared with resting values. While confirming the alliesthesial effect of exercise on thermal comfort during cooling, the present results also show that the intensity of local cold sensations is radically changed as a result of exercise.

Study 3 aimed to explore inter- and intra-segmental differences in thermal sensitivity to cold at rest and during exercise. Sixteen upper-body sites were individually stimulated using a 25 cm$^2$ thermal probe set at 20, 25 and 30°C.
Thermal sensations resulting from the stimuli were assessed using an 11-point cold sensation scale, and results were presented in body maps of thermal sensitivity. Variations were found within body segments, particularly at the upper and lower abdomen where the lateral regions were significantly more sensitive than the medial areas. Furthermore, mean thermal sensations were significantly colder at rest than during exercise in most body sites. Neural and hormonal factors were considered as potential mechanisms behind this reduction in thermal sensitivity. While confirming the effects of exercise on thermal sensitivity to cold, study 3 thus also provides evidence that thermal sensitivity to cold varies within body segments.

In study 4, thermal sensitivity to cold was compared between individuals of different ethnic origins (European, African and Asian). The protocol from study 3 was replicated, with this time the inclusion of lower body sites to create more complete body maps. Results revealed some dissimilarity between the ethnic groups in the distribution of thermal sensitivity across the body. Most differences found were between the British and the Chinese group, with colder sensations reported by Chinese participants.

Finally, study 5 offers a gender comparison of thermal sensitivity to cold, with the same protocol as study 4. The results showed that despite a similar pattern in thermal sensitivity to cold across the body, female participants reported significantly colder sensations than males did in several areas of the body.

The present PhD was co-funded by Oxylane Research, and several avenues exist for the application of the datasets created. The general idea of application behind this research was to adapt regional levels of clothing insulation according to local sensitivities to cold. Moreover, results of studies 2 and 3 may also be used for the improvement of physiological models, with the inclusion of the detailed distribution of thermal sensitivity to cold across the body, as well as the specific reductions in thermal sensitivity to cold resulting from exercise. Finally, results of studies 4 and 5 could be used for the creation of ethnic and gender-specific sports clothing.

**Keywords:** thermoregulation · thermal sensitivity · cooling · exercise · regional · alliesthesia · thermal comfort · ethnicity · gender.
Statement

The work presented in this thesis was funded by both Oxylane Research and the Department of Human Sciences of Loughborough University, which has now partially merged into the Loughborough Design School. The data collected in this research project has been and will be used by the Research and Development Engineers of Oxylane Research for the improvement of sports clothing and equipment, as well as for the improvement of their thermal manikin physiological model.

Study 1 was conducted jointly by the author and Mr Alistair Frizell in the context of his BSc. dissertation work. The author designed the experiment, collected the data with the student, and provided him with co-supervision. The data analysis presented in this thesis was independently done by the author.

Study 4 was conducted jointly by the author and Mr David Warmerdam in the framework of his MSc. Research Project. The author designed the experiment and provided support with the data analysis. The raw data was re-analysed by the author for inclusion in this thesis.

Finally, study 5 was conducted jointly by the author and Mrs Sarah-Jane O'Sullivan in the context of her BSc. dissertation work. The study was designed by the author, and co-supervision was also provided to the student. The data was re-analysed by the author before including it in this thesis.
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Chapter 1

Introduction and review of literature

1.1. Thermoregulation

1.1.1. The thermoregulatory system

Thermoregulation, or the maintenance of a stable core temperature ($T_c$) under a variety of external and internal conditions, is a key feature of human survival. In terms of thermal physiology, humans are tropical mammals. For a naked resting man, the thermoneutral zone is relatively narrow - between 25-27°C (Erikson et al. 1956). The thermoneutral zone indicates a range of ambient temperatures at which temperature regulation is achieved without regulatory changes in metabolic heat production or evaporative heat loss. Humans are also tachymetabolic homeotherms, meaning that the circadian and seasonal cyclic variations in $T_c$ are maintained within a relatively narrow range. Core temperature is in fact one of the most tightly regulated parameters of human physiology, and is typically maintained around 37°C (Guyton & Hall, 2000). A range exists however (35.5° - 40°C), which allows for variations induced by circadian and seasonal rhythms, physical activity, ambient temperature, food intake, age factors, menstrual cycle and emotional factors (Adair & Black, 2003). A body temperature outside this range indicates a disease state, unusual activity, or extraordinary environmental conditions, which can lead to physiological impairments and fatality (Moran & Mendal, 2002).

Thus, the temperature of deep areas of the body varies only to a minor extent with changes in environmental temperature. In contrast, temperature of the skin ($T_{sk}$) shows greater variations associated with environmental temperatures. The human thermoregulatory system is comprised of four main components: 1)
thermoreceptors, 2) neural pathways mediating afferent and efferent information to and from the central nervous system (CNS), 3) the controlling system located within the CNS, and 4) the thermoeffector system. The cutaneous thermal receptors act as an “early warning system” to relay sensory information to the hypothalamus and cortex. This input evokes appropriate heat-conserving or heat-dissipating physiologic adjustments resulting in the individual consciously willing to be relieved from the thermal challenge. In addition to receiving peripheral inputs, cells in the anterior portion of the hypothalamus detect slight changes in blood temperature. When these cells have an increased activity, other hypothalamic regions are stimulated which initiates coordinated responses for heat loss within the anterior hypothalamus or heat production/conservation within the posterior hypothalamus (Sherwood, 2010).

1.1.2. Thermal balance

The body heat balance equation is a mathematical expression describing the net rate at which the body generates and exchanges heat with its environment. The heat exchanges unit is watt (W), often also expressed in relation to the body surface area (W·m⁻²). In a steady-state situation, the heat produced by the body is balanced by the heat lost to the environment. The heat balance equation can be written as (Parsons, 2003):

\[ M \pm W = \pm R \pm C \pm K \pm S - E - RES \text{ [W·m⁻²]} \]

Where \( M \) is the metabolic rate, \( W \) is the rate of work produced by or on the body, \( R \) is the rate of radiant heat exchange with the surroundings, \( C \) is the rate of convective heat exchange with the surroundings, \( K \) is the rate of heat exchange by conduction, \( S \) is the rate of heat storage in the body (which should ideally be close to zero in order to prevent body temperature changes), \( E \) is the rate of heat loss due to evaporation of body water and \( RES \) is the rate of respiratory heat loss. In
order to achieve thermal balance, the transfer rate of heat from the surface to the environment must be equal to heat production. The four basic environmental variables affecting thermal balance are the ambient temperature, radiant temperature, air movements and humidity. Combined with metabolic heat production and clothing, these variables form the fundamental factors defining human thermal environments.

Wind can aggravate cooling under cold environmental conditions. The windchill equation takes into account the combined effects of temperature and wind and predicts the cooling of the bare skin (Wind Chill Temperature Index). Similarly, moisture due to precipitation/snowfall may cause wetting of clothing, which decreases its insulation value and potentiates cooling. Moisture may also originate from sweating, which also decreases the clothing insulation and enhances the heat loss. As the thermal conductivity of water is approximately 25 times that of air, heat loss is markedly increased by immersion into water. In contrast, radiation from the sun and different surfaces under sunny conditions is an external source of heat. Several individual factors also affect human thermal balance and the consequent thermal responses, such as gender, age, body size, fitness, and the amount of subcutaneous fat (e.g.: Budd et al. 1993, Havenith et al. 1995 & 2001, Van Ooijen et al. 2001, Stocks et al. 2004). In addition, other less obvious factors also affecting thermal balance include cardiovascular, endocrinological, muscular or neural disorders. Finally, the use of certain medication and drugs may pre-dispose individuals to cold stress, because of their effect on the fluid balance, vasoconstriction and/or dilation.

1.1.3. Heat loss and heat production

Human’s thermal balance is markedly affected by behavioural thermoregulation, which is often faster and more effective than the autonomic responses. Such actions include seeking a shelter, putting clothes on, taking them off, or exercising. These are especially important in extreme cold or hot environmental conditions. However, when these behavioural adaptations are not possible or not effective
enough, several physiological pathways exist to help the body to lose or gain heat. Heat loss mechanisms have been described in a review by Havenith (1999). A minor role is taken by *conduction*, mostly for people working in water, special gas mixtures, handling cold products or in supine positions. *Convection*, however, holds a more important role in heat loss. When air flows over the skin, it is usually cooler than the skin; as a result, heat will be transferred from the skin to the air around it. Furthermore, when a difference exists between the body’s surface temperature and the temperature of the surfaces in the environment, heat will be exchanged by *radiation*. Finally, the body possesses another avenue for heat loss, which is by *evaporation*. The human body has the ability to produce sweat, and as a result moisture appears on the skin and evaporates if the environmental conditions are favourable, causing large amounts of heat to be dissipated from the body. In addition to the convective and evaporative heat loss from the skin, these types of heat loss take place from the lungs by *respiration*, as inspired air is usually cooler and dryer than the lung’s internal surface. The heat loss avenues are summarised in Figure 1.1.

![Figure 1.1. Schematic representation of the pathways for body heat loss. M = metabolic heat production (Havenith, 1999)](image-url)
On the other hand, when excessive heat loss occurs, body heat production increases while heat losses are reduced to minimise any decline in core temperature. Constriction of peripheral blood vessels (vasoconstriction) immediately reduces the flow of warm blood to the body’s cooler surface and redirects it to the warmer core. For example, cutaneous blood flow averages 250 mL·min⁻¹ in a thermoneutral environment, yet with severe cold stress this flow can approach zero (Johnson, 1986). This response is mediated by the autonomic nervous system. During vasoconstriction, some blood is still allowed to flow in the more superficial parts of the body, but most of the circulation is directed to the inner parts of the body. These vascular changes reduce skin temperature of the peripheral areas toward ambient temperature, maximising the insulator benefits of the skin, muscle, and subcutaneous fat. A person with excessive body fat exposed to cold stress greatly benefits from this heat-conserving mechanism. At skin temperatures below 12°C, a sudden vasodilation occurs. This phenomenon is called cold-induced vasodilation (CIVD). During CIVD, blood flow to the extremities is increased, followed by an increase in skin temperatures (for a review on CIVD see Daanen, 2003).

Another major means of heat production is through changes in metabolic heat production. Metabolic rate indicates the transformation rate of chemical energy into heat and mechanical work by aerobic and anaerobic metabolic processes. Most of the metabolic energy (>80%) is released as heat and about 0 to 20% is used for mechanical work. The basal metabolic rate (BMR) of a medium-sized adult is estimated at 41 W·m⁻² for women and 44 W·m⁻² for men (ISO 8996). Metabolic rate greatly varies however, and it is related to environmental conditions, clothing, level of activity, as well as several individual characteristics. A decrease in environmental temperature increases the energy expenditure of resting subjects. For example, a decrease from 22°C to 16°C results in an increase in energy expenditure by 116 kJ·°C⁻¹ on average (Westerterp-Plantenga et al. 2002). Furthermore, eating increases metabolic rate for several hours, and the effect of a single meal results in an increase of approximately 20% above BMR (Karst et al., 1984; Cannon & Nedergaard, 2004). The activation of the sympathetic nervous system also affects
the metabolic rate. Cooling of the peripheral areas and other thermosensitive structures stimulates the preoptic area in the hypothalamus from where efferent information via α-motor neurons is mediated to the muscles, causing an increase in thermoregulatory muscle tone. If the cooling continues, the thermoregulatory muscle tone is superimposed by microvibrations; Shivering is defined as an “involuntary tremor of skeletal muscles as a thermo-effector activity for increasing metabolic heat production” (IUPS, 2001). In mild shivering, the contractile activity of the motor units is periodical, while in more severe shivering, it is continuous. This increases metabolic rate 2-5 times above basal levels. However, this increase is relatively small and surprisingly ineffective when compared with that produced by exercise (10 fold). The metabolic rate increases also through non-shivering thermogenesis (NST). NST is defined as heat production due to metabolic energy transformation by processes that do not involve contractions of skeletal muscle (i.e. shivering). In NST, heat is generated through special uncoupling proteins situated in the brown adipose tissue (BAT). BAT is richly innervated with sympathetic nerves. UCP-1 is a mitochondrial channel protein allowing the influx of protons into mitochondria and uncoupling oxidative phosphorylation. In this process, heat is produced instead of ATP. Relatively large deposits of brown adipose tissue can be found in new-borns; however, in adult persons the heat production through NST is often insignificant, but may be activated if the exposure to cold is chronic (Cannon & Nedergaard, 2004).

1.1.4. Core temperature

As described in earlier in this chapter, complete and proper functioning of the body is dependent on maintaining an internal temperature close to 37°C. Several methods and measurement sites are used for core temperature (Tc), and although considerable regional variations exist, most research uses a single site for its measurement.
$T_c$ is essentially the temperature of the blood in the circulation, and the gold standard for $T_c$ measurement is the temperature of the blood from the pulmonary artery (Farnell et al., 2005). The pulmonary artery receives blood returning to the heart through the right ventricle, which is the blood that stores and transports heat to the skin and to the various organs in the body (Lim et al., 2008). Fluctuations in $T_c$ can have significant implications on homeostasis in the body. Hyperthermia ($T_c > 42^\circ C$) can be detrimental to cellular and organ functions, which can impair the central nervous system and multiple organ failures (Bouchama & Knochel, 2002). Hypothermia ($T_c < 35^\circ C$) impairs cardiovascular, respiratory and central nervous system functions, which can lead to muscle damage, pulmonary oedema, hypotension and renal failure (Brukner & Khan, 2005). The strong association between $T_c$ and physiological homeostasis makes $T_c$ an important clinical and laboratory indicator of thermal strain in the body.

Before the existence of the thermometer in the 18th century, physicians were skilled in assessing $T_c$ by feeling skin temperature with their hands (Moran & Mendal, 2002). The significance of thermometry for the clinical diagnosis of fever was only recognised in 1868 (Wunderlich, 1871). The current gold standard for $T_c$ is the temperature within the pulmonary artery (Farnell et al., 2005), but measurement of intra-pulmonary arterial (IPA) temperature is invasive and is not suitable for non-surgical applications. In humans, non-invasive surrogate measurement of $T_c$ is commonly taken at the sublingual site (oral temperature), the axilla, and the tympanic membrane (Lim et al, 2008). More invasive sites for surrogate measurement of $T_c$ include the rectum, oesophagus, and the GI tract. Temperature readings from these $T_c$ measurement sites are not uniformed because they represent the local temperature of the respective anatomical sites (El-Radhi & Barry, 2006). The site of choice for $T_c$ measurement would depend on the type of instrument available and used, and the purpose of measurement. Sublingual, axilla and tympanic temperatures are commonly used in the clinical setting, whereas rectal, oesophagus and GI temperatures are most commonly used in laboratory experiments. In the present project, the most appropriate measurement was rectal temperature, as it provides a reliable measure of $T_c$ while allowing participants to easily perform exercise (Farnell et al., 2005).
1.2. Thermal sensation

1.2.1. Definitions

Perceptions evoked by thermal stimulation can be divided into two types: “temperature sensation” and “thermal comfort” (Hensel, 1981). Sensation is defined as the conscious or subconscious awareness of the external or internal environment (Tortora & Derrickson, 2005). This definition can be applied to all somatic sensory modalities: tactile sensations (touch, pressure, and vibration), pain sensations, proprioceptive sensations, and thermal sensations (warm and cold).

1.2.2. The process of sensation

The human skin acts as both a sensory organ and a protective organ. Thermoreceptors are free nerve endings which can either be “cold” or “warm” types, according to their responses to thermal stimuli. Skin thermoreceptors are located in the dermis at an average depth (from the surface of the skin) of 0.15 to 0.17 mm for cold receptors and 0.3 to 0.6 mm for warmth receptors (Hensel, 1982), and it has been suggested that there are around ten times more cold receptors than warmth receptors (Guyton & Hall, 2000). Recent knowledge suggests that the principal temperature sensors in the nerve endings belong to the transient receptor potentials (TRP) which are activated by distinct temperatures, and are involved in converting thermal information into chemical and electrical signals within the sensory nervous system (Schepers & Ringkamp, 2008). The main transduction mechanism for cooling occurs possibly via a cold- and menthol-activated ion channel (TRPM8) (Reid, 2005). In addition, four TRPV channels are activated by heating (TRPV1-4).

At constant temperatures, cold and warm receptors have characteristic temperatures for maximum static discharge frequency. For cold receptors, this ranges between 20 and 30°C, and for warm receptors between 40 and 47°C. A paradoxical discharge in cold receptors is also observed above 45°C. The rate of
change in skin temperature critically influences sensory responses. Both warm and cold receptors increase in firing rate when temperature changes, but quickly become adapted when the temperature is kept constant (Kenshalo, 1970; Hensel, 1981). The faster the rate of increase in stimulus energy, the faster the firing frequency for receptor response (Kenshalo & Duclaux, 1977). The derivative of skin temperature has a stronger influence on sensation than skin temperature itself, because the firing rate of thermoreceptors is 5 – 10 times higher during a change in temperature than under steady conditions (Hensel, 1982). Physiologically, this is explained by the adaptive capabilities of thermoreceptors. When an abrupt change in temperature occurs, it is first strongly stimulated, and impulses are therefore sent at a high frequency. But this stimulation decreases rapidly during the first seconds following the temperature change, and then progressively more slowly until it reaches a steady level (Figure 1.2). As a result, when the temperature is actively falling or rising, a person feels respectively colder or warmer than when the temperature remains the same. This overreaction observed during transient exposures has been termed ‘overshoot’ (Gagge et al., 1967). Figure 1.2 illustrates that in any change of conditions, the sensor firing rate overshoots its new equilibrium value, thereby passing a strong signal of change to the brain.

Figure 1.2. General properties of thermoreceptors. Static and dynamic responses of warm and cold receptors to constant temperatures and temperature changers (Hensel, 1982).
Information from cutaneous thermoreceptors, as well as the internal thermoreceptors, is integrated at the preoptic area of the hypothalamus. Conscious perceptions of thermal sensation and thermal comfort are then integrated in the cerebral cortex, where a specific region exists for each type of perception. The cerebral cortex then interprets these as coming from the stimulated sensory receptors, which is then perceived in a certain way depending on previous experiences.

### 1.2.3. Measurement of thermal sensation

In order to assess thermal sensations in humans, scientists have developed subjective scales, thereby providing useful measurements related to the perceived thermal state of individuals. Since Houghten and Yaglou (1923) began the study of thermal discomfort, a number of scales have been developed. These have typically been formatted as categorical scales (CS), also known as Likert scales. Likert scaling is usually presented as a 4-11 point scale which includes verbal descriptors designated for each point, anchored at each end by the extreme of the construct. Additionally, researchers have also developed visual analog scales to measure thermal perceptions. The original term “visual analog scale” (VAS) has been defined as a straight line, the ends of which are the extreme limits of the measured sensation (Scott and Huskisson, 1976). The CS and VAS which have most frequently been used for the measurement of thermal perceptions are illustrated in Figure 1.3.

There are several pros and cons of using CS and VAS. The rationale for using VAS is that individuals have greater accuracy in conveying their subjective experiences if they are not artificially forced to make ratings according to restricted verbal categories (Leon et al., 2008). On the contrary, the rationale for using CS is that verbal descriptors may help people to convey their subjective experiences (Lee et al., 2010b). Although it has been suggested that “words may fail to describe the exactness of the subjective experience” (Aitken, 1969), Lee et al. (2010b) indicated that perceived thermal sensations are conveyed more accurately with verbal
descriptors than without. Due to the non-restricted scoring system, variances for the scores on VAS are greater than those for the Likert scale, which is often interpreted as VAS offering a greater sensitivity than categorical scales. However as specified by Lee et al. (2010b), the sensitivity of a scale for the measurement of thermal sensation should be considered both by the number of units on a scale and the discriminatory ability of the human mind together. Indeed, CS with a low number of anchors may be too small to discriminate our thermal sensations in some cases, but invisible-infinite categories on VAS may be too abundant to project our limited thermal sensation (Lee et al., 2010b).
Figure 1.3. Current scales for measurement of subjective perception of thermal sensation. (A) Koscheyev et al. (2000) and Hoffman and Pozos (1989); (B) Lee et al. (2010b); (C) Frank et al. (1999, 2000); (D) Arens et al. (2006) and Davey et al. (2007); (E) Greenspan et al. (2003); (F) Hollies (1977); (G) Taylor N, modified after Gagge et al. (1967); (H) Winakor (1982); (I) ISO 10551 (1995); and (J) Nagano et al. (2005).
1.3. Thermal comfort

1.3.1. Definitions

Thermal comfort and discomfort are “pleasant” and “unpleasant” emotional feelings which can phenomenologically be discerned from temperature sensations (Hensel, 1981). Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment” (ASHRAE, 1966). Thus, while thermal sensation is the fundamental perception of temperature triggered by internal and cutaneous thermoreceptors, thermal comfort is related to the affective interpretation of thermal sensations, and is a major determinant driving our behavioural thermoregulation. Fanger (1970) outlined the conditions necessary for thermal comfort, as well as the methods and principles of evaluating and analysing thermal environment with respect to thermal comfort. He defined three conditions for a person to be in (whole body) thermal comfort:

- the body is in heat balance
- sweat rate is within comfort limits
- mean skin temperature is within comfort limits

Furthermore, absence of local discomfort is also required. Local cold discomfort may rise from draughts, thermal asymmetry or contact with cold surfaces.

1.3.2. Mechanisms of thermal comfort

Thermal comfort and discomfort are important for temperature regulation, since it drives an individual to search for the appropriate thermal environment or to change the behaviour or position in order to maintain an optimal body temperature. Physiologically, it is generally assumed that inputs from the same warm or cold skin thermoreceptors are utilised for both temperature sensation and thermal comfort, although there is no direct experimental evidence for this supposition. Specifically, it has been suggested that thermal comfort is largely influenced by skin
temperature when core temperature is constant (e.g.: Marks & Gonzalez, 1974), but is also dependent on body core temperature when changing (e.g.: Mower, 1976).

Discomfort may be caused by the body being too warm or cold as a whole, or by unwanted heating or cooling of a particular part of the body causing local discomfort (Hensen, 1990). It has been suggested that the highest levels of thermal pleasantness are associated with transient conditions, and are of short duration (Kuno, 1995). Thermal comfort can thus be seen as a lack of discomfort in steady state conditions (Parsons, 2003). While the neuronal mechanisms of thermal comfort are poorly understood, the amygdala, mid-orbitofrontal and pregenual cingulate cortex, striatum, and cerebellum have been implicated in the genesis of thermal comfort (Kanosue et al., 2002; Sung et al., 2007; Rolls et al., 2008).

### 1.3.3. Measurement of thermal comfort

Thermal comfort appears to be a psychological phenomenon, not always directly related to physical environment or physiological state. Similarly to thermal sensation, thermal comfort is usually measured with categorical scales. While the most common scales only have one “positive” category (“comfortable”), McIntyre (1981) suggested that there can be situations where one feels pleasantly cool or warm. This was confirmed by Humphrey and Nicol (2004), who showed that people prefer sensations on the warm side of the neutral if it is cool outdoors, and vice versa. As a result, thermal comfort scales were recently developed and include anchors such as “slightly comfortable” and “very comfortable” (e.g.: Zhang, 2003). Humans have little problem discerning local from whole-body thermal comfort. For example, during cold exposure whole-body thermal discomfort may remain despite inducing thermal comfort in one part of the body by warming it up (Nakamura et al., 2008).
1.4. Thermal sensitivity

1.4.1. Definitions

In thermal physiology, thermal sensitivity can be measured with different methods, resulting in different measures which must therefore be interpreted appropriately. Several definitions therefore exist for thermal sensitivity, according to the method used. While each method has in common the application of a thermal stimulus and some form of response from individuals, there are fundamental differences in the protocol used. The 3 main methods of thermal sensitivity are measurements of: (1) thermal spots density, which is an indirect estimation of thermoreceptors density; (2) thermal thresholds, which are the upper and lower limits for perception of cold or warm thermal sensations; and (3) thermal intensity rating which is the estimation of the level of cold or warmth in response to a given stimulus. These three methodologies are described in more detail in the next sections.

1.4.1.1. Thermal spots density

It is widely established that during a thermal stimulus, the information flow from peripheral thermoreceptors depends on the intensity of stimulation. This activity is determined by the absolute value and rate of change of temperature, as well as by the number of stimulated thermoreceptors (Kozyreva, 2006). It would be practically impossible to assess the number of functioning thermoreceptors during a thermal stimulation because of their size. The measurement of cold and hot spots allows a non-invasive estimation of thermoreceptors density. Cold and hot spots are areas on the skin which are perceived when stimulated with a cold or warm stimulus, respectively. Electrophysiological experiments have established that every cold or hot spot with a diameter of 1 mm is innervated by at least one thermoreceptor (Kenshalo & Gallegos, 1967; Hensel et al., 1974; Kenshalo, 1984). Therefore, the distribution of thermoreceptors can be estimated in humans by measuring the distribution of thermally sensitive spots. The number of sensitive
cold or hot spots has been deemed to characterise the temperature sensitivity in humans (Kozyreva, 2006). Early studies investigating thermal sensitivity used the method of sensory spots which is an indirect measurement of warm or cold thermoreceptors’ densities. The procedure consists of individually applying a small (usually 1 mm²) thermostimulator in many neighbouring points within a small surface area of a body region. For each point, subjects report whether or not the thermal stimulus is perceived (yes or no score), allowing calculation of the number of cold and warm “spots” per surface area. Although the number of thermal spots is not necessarily equal to the absolute number of thermoreceptors, this method is useful for a proportional comparison of thermoreceptors distribution across different body regions (e.g.: Rein, 1925; Struhold and Porz, 1931) as well as between genders or age groups (e.g. Choi et al., 2001).

1.4.1.2. Thermal thresholds

It is important to distinguish the difference between absolute threshold, difference threshold and terminal threshold. The absolute threshold, also referred to as detection threshold, is the highest stimulus temperature capable of producing a cool sensation (cool threshold) or the lowest stimulus temperature capable of producing a warm sensation (warm threshold). The absolute threshold can thus be seen as the highest temperature perceived as cool (cold threshold), or the lowest temperature perceived as warm (warm threshold). Absolute thermal thresholds are measured with the method of limits, which consists of exposing a participant to a stimulus of changing intensity, starting from a neutral temperature. It is crucial that the stimulus temperature changes with a low and constant rate of change, as the measurement would be otherwise inaccurate due to the important influence of rate of change in temperature on thermoreceptors’ activity (1.2.2). The participant is asked indicate the first onset of a cool or warm sensation. In this method, the measure is the amount of stimulation (i.e. the temperature of the stimulator) needed for a person to perceive the stimulus 50% of the time (Meilgaard, 2007). This test is then also administered from a point somewhat above threshold to a point where sensation disappears, and threshold is taken as a point midway
between the two values obtained (Yarnitsky and Fowler, 1997). Typical values of cool and warm absolute thresholds are respectively around 33 and 37°C (Lee et al., 2010a) although the values differ according to stimulus size and body site tested. The effect of body location will be discussed further in the literature review.

One limitation of the method of limits is that a reaction time artefact exists, which increases the value of the absolute threshold considerably (Yarnitsky & Ochoa, 1990). Reaction time artefact is larger for warming than cooling since the primary afferents are slower conducting, and is most extreme for distal body sites. It can however be diminished by using a slow rate of temperature change (Yarnistky & Ochoa, 1990). Furthermore, another disadvantage of this method is that the subject may become accustomed to reporting that they perceive a stimulus and may continue reporting the same way even beyond the threshold (error of habituation). Conversely, the subject may also anticipate that the stimulus is about to become detectable or undetectable and may make a premature judgement (error of expectation) (Meilgaard et al., 2007).

The difference threshold is the extent of change in the stimulus necessary to produce a noticeable difference. It is thus measured in the same way as the absolute threshold described above, but is presented as a change in temperature from neutrality needed to provoke a cool or warm thermal sensation. Typical values of cool difference threshold are between 1 and 2 °C, while warm difference thresholds are between 2 and 4°C, depending on the body location tested (Lee et al., 2010a). Finally, the terminal threshold is the magnitude of a stimulus above which there is no further increase in the perceived intensity of the appropriate nature of that stimulus. For example, if thermal sensation values increase with an increasing stimulator temperature up to 40°C, but do not increase any further, then the terminal threshold is 40°C. Above the terminal thermal threshold level, pain usually occurs.

Thus, in the method of limits, the participant is exposed to a stimulus of increasing intensity and then asked to indicate the first onset of sensation during the change in
stimulus temperature. In contrast, in the method of levels, a stimulus of pre-determined intensity and duration is delivered to the subject who responds post factum. For the measurement of cool threshold, the thermal stimulator is initially set at an adaptation (neutral) temperature and applied onto the skin. It is then set to a pre-determined cool temperature (e.g.: 18°C). As a binary decision task, the subject is asked to say ‘yes’ or ‘no’ as to whether the stimulus is felt. The stimulus then returns to the adaptation temperature. The next stimulus is increased by a fixed increment (e.g.: 0.5°C) compared with the first stimulus. This procedure is repeated until the cool sensation can no longer be perceived. The temperature midway between the highest un-perceived stimulus and the lowest perceived stimulus is taken as the thermal threshold.

1.4.1.3. Thermal intensity rating

Two additional measurements of thermal sensitivity exist, both related to a similar experimental protocol. The method of magnitude estimation (Stevens, 1975) requires subjects to estimate the magnitude of physical stimuli by assigning numerical values proportional to the stimulus magnitude they perceive. To help better understand this technique, these are the instructions given to participants prior to the start of a magnitude estimation of cold stimuli (Stevens, 1979):

“Objects of various temperatures will be briefly touched one by one to each area. Your task is to judge each time the degree of coolness as you experience it. (...) To the first stimulus assign any number you deem appropriate to stand for the amount of coolness you experience. Then to subsequent stimuli match numbers to their coolness. If you give the first stimulus the number “n”, then if the second feels five times as cold assign the number 5n; if 1/5 as cold, then n/5. You may use any number including decimals, fractions and large numbers. The scale has no upper or lower boundary, except that zero would mean no cold experienced at all. Remember that you are to judge the amount of cold sensation, not the temperature”.
Alternatively, a less complex approach to thermal intensity rating involves the use of a fixed thermal sensation scale, such as the ones depicted in Figure 1.3. This method is especially useful when larger areas of the body are cooled, such as full body segments (*local thermal sensation*) or even whole body (*overall thermal sensation*). This then allows calculation of thermal sensitivity as a change in thermal sensation per change in skin temperature (e.g.: Cotter, 1997). This method takes into account the total change in temperature which may not be easy to accurately control during cooling. This measurement of thermal sensitivity is not limited to local thermal sensation (LS), but can also be applied to overall thermal sensation (OS), local thermal comfort (LC), and overall thermal comfort (OC). These are mathematically expressed respectively as: $\Delta \text{LS}/\Delta T_{sk}$, $\Delta \text{OS}/\Delta T_{sk}$, $\Delta \text{LC}/\Delta T_{sk}$, $\Delta \text{OC}/\Delta T_{sk}$. Each of these equations provide a different definition to the concept of thermal sensitivity which must be interpreted accordingly. This will be discussed in more depth further in the thesis.

### 1.4.2. Regional distribution in thermal sensitivity

#### 1.4.2.1. Small thermal stimuli

The sensitivity of temperature sensation is not uniform, but rather it depends on the body region. The regional distribution of thermal sensitivity in the skin is an important question in connection with temperature sensation, autonomic temperature regulation, thermal comfort and thermoregulatory behaviour (Hensel, 1981). The variations in thermal sensitivity to warm and cold according to body site are presumably due to a non-uniform distribution of cutaneous receptor density (Yarnitsky & Fowler, 1997). If thermoreceptor distribution does differ in various regions of the body, these regions may be of different importance for eliciting sensory or regulatory responses, even when the surface areas of the stimuli are equal. Several authors have measured thermal spot density at multiple body sites, allowing for comparisons of regional distributions in thermoreceptor densities. These are presented in Table 1.1.
<table>
<thead>
<tr>
<th></th>
<th>Cold spots</th>
<th>Cold spots</th>
<th>Warm spots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strughold and Porz, 1931</td>
<td>Choi &amp; Seol, 2001</td>
<td>Rein, 1925</td>
</tr>
<tr>
<td>Forehead</td>
<td>5.5-8.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nose</td>
<td>8.0</td>
<td>-</td>
<td>1.0</td>
</tr>
<tr>
<td>Lips</td>
<td>16.0-19.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Face - Other parts</td>
<td>8.5-9.0</td>
<td>10.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Chest</td>
<td>9.0-10.2</td>
<td>6.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Abdomen</td>
<td>8.0-12.5</td>
<td>6.6</td>
<td>-</td>
</tr>
<tr>
<td>Back</td>
<td>7.8</td>
<td>6.6</td>
<td>-</td>
</tr>
<tr>
<td>Upper arm</td>
<td>5.0-6.5</td>
<td>5.4</td>
<td>-</td>
</tr>
<tr>
<td>Forearm</td>
<td>6.0-7.5</td>
<td>5.3</td>
<td>0.3-0.4</td>
</tr>
<tr>
<td>Back of hand</td>
<td>7.4</td>
<td>3.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Palm of hand</td>
<td>1.0-5.0</td>
<td>1.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Finger dorsal</td>
<td>7.0-9.0</td>
<td>-</td>
<td>1.7</td>
</tr>
<tr>
<td>Finger volar</td>
<td>2.0-4.0</td>
<td>-</td>
<td>1.6</td>
</tr>
<tr>
<td>Thigh</td>
<td>4.5-5.2</td>
<td>6.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Calf</td>
<td>4.3-5.7</td>
<td>3.1</td>
<td>-</td>
</tr>
<tr>
<td>Back of foot</td>
<td>5.6</td>
<td>2.4</td>
<td>-</td>
</tr>
<tr>
<td>Sole of foot</td>
<td>3.4</td>
<td>1.0</td>
<td>-</td>
</tr>
</tbody>
</table>

Moreover, several studies used the method of limits to investigate the distribution of thermal sensitivity across the body. As described earlier in this chapter, this method provides a measurement of perceptual thermal thresholds. In their study, Greenspan and colleagues (1993) analysed absolute thresholds for the perception of coolness at four body sites (hand, forearm, foot, leg). Their results indicated that cool absolute threshold were highest (highest sensitivity) at the hand, intermediate for the forearm and lowest for the leg and foot. In a more recent study, Lee and colleagues (2010a) investigated ethnic differences in thermal thresholds at 12 sites across the body, using a 6.25 cm² thermal stimulator. Regarding regional differences, their results showed that the initial perception of a cool sensation occurs at different absolute skin temperatures (absolute thresholds) depending on the body location. Furthermore, regional differences were also found in difference thresholds, meaning that the initial perception of a cool sensation occurred after
different degrees of change in skin temperature depending on the body region stimulated. Body regional differences were more marked in warm thresholds than cool thresholds. The difference thresholds for detection of cool sensations were significantly lower (i.e. higher sensitivity to cold) at the forehead than at the upper back, calf, and foot sites.

Regarding thermal intensity rating methods, Stevens (1979) assessed the differences in thermal sensitivity to cold across the body, using the method of magnitude estimation with a 20 cm$^2$ temperature regulated stimulator set at different temperatures between 0 and 30°C. Results showed that the sub-regions of the trunk were most sensitive to low and medium levels of stimulation, followed by those of the limbs and then those of the head. However the differences among the regions diminished with increasing stimulus temperatures, and finally almost disappeared when the magnitude of the cold sensation approached a “ceiling”.

### 1.4.2.2. Large thermal stimuli

Instead of using small metallic stimulators, several researchers have used larger water-perfused patches, or even water-perfused suits. There are several advantages of using such equipment. The main one is the ability to cool down or warm up a large body area. This does not only evoke thermal sensations, but also perceptions of thermal comfort or discomfort, which cannot easily be assessed with small thermal probes. Furthermore, these larger stimuli have a marked impact on whole-body perceptions. This therefore brings another dimension to the exploration of thermal sensitivity, that of the influence of a local thermal stimulus on overall thermal sensation and thermal comfort. This measure of thermal sensitivity can be mathematically defined as $\Delta OS/\Delta T_{sk}$, $\Delta OC/\Delta T_{sk}$. This may be more relevant than simply measuring the intensity of local perceptions, at least for the applied side of research, as one body segment may be seen as thermally sensitive according to local thermal perceptions without necessarily provoking an intense overall thermal sensation and/or discomfort value.
Cotter (1997) compared thermal sensitivity to cold and warmth at ten regions using water-perfused patches. Two main variables are investigated in Cotter’s thesis; temperature sensation sensitivity and physiologically-related (sweat) thermal sensitivity. The main experiment consisted of thirteen males resting supine during warming (W+4°C), as well as mild (C-4°C) and moderate (C-11°C) cooling of ten skin sites matched for surface area (274 cm²). The warming and cooling of each zone was done individually with cooling patches, whilst core and the remaining body sites were clamped above the sweat threshold using a water-perfused suit (WPS). Local skin temperature was obtained beneath the water-perfused patches using five surface skin thermistors for which the mean Tsk was calculated using a numerical average. The local warming was always done first for 10 minutes, after which the moderate cooling was applied for 5 minutes to achieve a ∆Tsk of -11°C from the elevated W+4°C skin temperature level, at a maximal rate of -8°C/min. A 10 minute recovery period was then provided, during which the re-attainment of baseline Tsk was achieved. Finally, the C-4°C treatment was done.

During the trials, temperature sensation and thermal discomfort data were obtained using a modified version of Gagge’s scales (1967), respectively ranging between 1.0 (Unbearably cold) and 13.0 (Unbearably hot) for thermal sensation, and 1.0 (Comfortable) and 5.0 (Extremely uncomfortable) for thermal comfort. Local thermal sensitivities were calculated from changes in thermal sensation and thermal discomfort, relative to ∆Tsk. Localised warming and cooling from the local elevated adapting temperature of 36.3°C caused not only appropriate localised changes in temperature sensation, but also shifted the whole-body sensation in the same direction. Similarly, local and whole-body thermal discomforts were significantly increased during W+4°C, and decreased during C-4°C and C-11°C, with the exception of a non-significant decrease in whole-body discomfort during C-4°C. Regarding comparisons between body sites, significant inter-regional differences in local temperature sensation and thermal discomfort were apparent for both W+4°C and C-11°C; these are illustrated in Figure 1.4. Most relevant to the present literature review was the finding that the foot, head and hand were consistently the most sensitive regions in terms of C-11°C.
Figure 1.4. Thermal sensitivity results in terms of temperature sensation and thermal comfort (Cotter, 1997). Values presented are Means (± SE) change in local (A) and whole-body (B) temperature sensation and local (C) and whole-body (D) thermal discomfort, after 4 min of mild warming (W+4), equivalent cooling (C-4) or moderate cooling (C-11) at each of ten localised skin regions. Data were divided by the change in the intra-patch skin temperature after 4 min. Thus, a cooler sensation or a decrease in discomfort during cooling are positive values, allowing a comparison between warming and cooling influences. C-11 was applied at the completion of W+4.
In a more recent study, Nakamura et al. (2008) used a similar methodology to Cotter’s (1997), investigating regional differences in temperature sensation and thermal comfort. Participants sat in an environment of mild heat or cold and while being simultaneously locally cooled or warmed with water-perfused stimulators of 270 cm² (Figure 1.5).

![Figure 1.5. Thermal stimulators used by Nakamura et al. (2008). Left is for the face, and right is for the other areas](image)

Each stimulation lasted 90 s, and four different body regions were individually stimulated: face, chest, abdomen and thigh. $T_{sk}$ was recorded at two locations under each stimulation device. Temperature sensation and thermal comfort of the stimulated areas were reported by the subjects, as well as whole-body thermal comfort. This was done in the period from 120 s before, to 90 s after each local stimulation, whenever any change in the sensations was felt. Thermal sensation and comfort were reported by rotating dials located in front of the subject and numbered from -10 (“maximal cold” or “maximal uncomfortable”) to +10 (“maximal hot” or “maximal comfortable”); 0 indicated “neutral.” Nakamura’s results showed that during mild heat exposure, cooling caused a positive thermal comfort at all 4 segments tested. Facial cooling was perceived as significantly more comfortable than abdomen cooling, but no other significant differences were found between regions. In contrast, during mild cold exposure, cooling elicited negative thermal
comfort values. Local thermal discomfort was most pronounced at the thigh and abdomen and least at the face where the cooling caused practically no thermal discomfort. Regarding local warming during mild cold exposure, local warming of the chest and abdomen produced a strong comfort sensation, and this effect was found to be more prominent for the abdomen than for the chest.

In contrast to the use of conductive thermal stimulators, Zhang (2003) used a convective stimulus consisting of conditioned air sleeves enclosing the targeted body segment. The tests were designed to force local skin temperatures through a range of values. The following 19 body segments were tested: head, face, neck, breathing zone, chest, back, pelvis, left and right upper arms, left and right lower arms, left and right hands, left and right thighs, left and right lower legs, left and right feet. The entire surface of a body segment was cooled or heated using a sleeve (examples shown in Figure 1.6). Within each segment, skin temperatures were measured by at least one thermocouple, positioned at standardised locations.

![Figure 1.6. Air sleeves used in Zhang’s research (2003)](image)

Most of the tests involved cooling a body part under warm conditions, and then removing the sleeve and allowing the local part to warm up to its initial temperature. A smaller number of tests warmed a body part under cool conditions, followed by cooling recovery. Both types of tests produced data for analysing
cooling and warming transient responses. Unfortunately, the authors did not reveal any experimental data such as means, neither in publications (e.g. Arens et al., 2006) nor in Zhang’s thesis (2003). Instead, they provided examples of patterns which they consistently found in their experiments and describe the creation of mathematical models allowing predictions of both local and overall thermal sensation and comfort. Zhang (2003) suggested that body parts can be divided into three groups according to their influence on whole-body thermal sensation: most influential, least influential and moderately influential. The most influential group consists of the back, chest, and pelvis. Sensation from these body parts had a dominant impact on overall sensation; in fact, the overall sensation closely followed local sensation during the cooling/heating and recovery process at these body segments. In contrast, the least influential group includes the hand and the foot. Local changes in $T_{sk}$ at these body parts have a very small impact on overall body thermal sensation. Finally, all areas of the head, arms and legs belonged to the “moderately influential group”. The behaviour from these body segments fell between the two groups above. It must be noted at this stage that Zhang’s so-called thermal sensitivities were based on changes in thermal sensation and comfort intensity only, without taking into account the relative change in $T_{sk}$ during the experiments. It is therefore possible that the “groups” of thermal sensitivities may have been different if adjusted for the total change in local $T_{sk}$. Since mean data are not presented by Zhang, it is difficult to gauge to what extent this may have influenced the groups described above.

Although these studies provide relevant data in terms of the distribution of regional sensitivity at different body segments, none has systematically compared thermal sensitivity to cold at whole body segments starting from a neutral state. Comparing thermal sensitivity in relation to both thermal sensation and thermal comfort will therefore be the first main aim of the present thesis. Additionally, it is often assumed that thermal sensitivity is uniform within body segments, although no previous study has explored intra-segmental differences in thermal sensitivity to cold. This will therefore be the second main objective in the present thesis.
1.4.3. The effects of exercise on thermal sensitivity

1.4.3.1. Small thermal stimuli

As described in previous sections, peripheral thermal stimuli can arouse an affective perception (e.g.: pleasure/displeasure or comfort/discomfort) as well as an intensity perception (e.g.: neutral/cool/cold thermal sensation). Regarding the affective perception, Cabanac (1969) defined thermal alliesthesis as the pleasure or displeasure sensation aroused by a given peripheral thermal stimulus, according to the internal thermal state of a subject. For example, warming the hand produces a comfortable or uncomfortable feeling when the individual is respectively “hypothermic” or “hyperthermic”. A thermal stimulation is thus felt comfortable when it serves to regain appropriate body temperature, and felt uncomfortable when it worsens internal thermal conditions.

Attia and Engel (1982) investigated the thermal pleasantness of a set of temperature stimuli (15 cm²) in different conditions, and found that thermal alliesthesis occurs as a result of both exogenous (i.e. passive thermal exposure) and endogenous (i.e. exercise) thermal loads. In contrast, regarding the intensity component of thermal perceptions, Mower (1976) showed that thermal sensations resulting from a given thermal stimulus was not affected by passive thermal loads. To the best of our knowledge, no study has investigated the effects of endogenous thermal loads (i.e. exercise) on the intensity of a thermal sensation resulting from a given thermal stimulus. The effects of exercise on thermal sensitivity have however been approached with the method of limits by Kemppainen and colleagues (1985), who explored the modification of cutaneous thermal thresholds during and after physical exercise. The present review will concentrate on the latter part of the study. Five healthy male participants took part in the experiment consisting of two sessions. The method of limits was used with a 3.8 cm² thermostimulator, and skin temperature was recorded 5 cm from the thermal sensitivity measurement sites. Both warm and cool thresholds were measured, allowing calculation of the intervals between warm and cool thresholds referred to as thermal limens. Thermal
thresholds were measured at the hand, forearm and leg in three conditions: at rest, whilst cycling (100, 150, 200 and 250 W) which was tested at two pedalling frequencies, and after 15 min of recovery. Results showed that the initial perception of a cool sensation occurred at a lower skin temperature during exercise compared to rest, and similarly, the initial perception of a warm sensation occurred at a warmer skin temperature during exercise. This resulted in a significant increase in thermal limens in the exercise conditions. This effect increased as a function of exercise intensity, and was most marked at the leg and least at the glabrous hand, with an intermediate value found at the forearm. No significant effect was found on the effect of pedal frequency. After 15 min of post-exercise recovery, thermal limen values returned close to the initial resting levels. Results at the hand are illustrated in Figure 1.7 as an example.

![Figure 1.7. Average thermal limens (= neutral zone between warm and cool thresholds) in the hand at different workloads. The solid line shows 40 rpm; dotted line shows 70 rpm. Vertical bars represent ± S.E. From Kemppainen et al. (1985).](image)

Kemppainen’s results provide thermal threshold scores at rest and during exercise; however, the effects of exercise on thermal sensation intensity scores in response
to a given cold stimulus rather than on thresholds remain unknown. Furthermore, the limited number of body locations tested provides little information on the distribution of the changes in thermal sensitivity resulting from exercise.

**1.4.3.2. Large thermal stimuli**

Regarding whole-segments or even whole-body cooling, limited knowledge is currently available on the effects of exercise on thermal sensitivity to cold. In fact, while a large body of research exists on pre- and post-exercise body cooling, only little is known on the effect of skin cooling *during* exercise, particularly in terms of thermal sensation and thermal comfort. Shitzer (1973) carried out an interesting study primarily undertaken to explore the preferred local coolant inlet temperatures at different body segments of a water-perfused suit (WPS). This work was done with astronauts’ thermal comfort and cooling efficiency in mind. A bespoke WPS was used, consisting of 16 individual pads of identical size made of tygon tubes, covering the head, torso, arms, thighs and legs. The face, neck, hands and feet were not covered with cooling tubes. These pads were stitched onto the inside of a garment. The body was cooled in six separate regions with a total of 16 pads distributed as follows: head (2 pads), upper torso (2 pads), lower torso (2 pads), arms (4 pads), thighs (4 pads), and lower legs (2 pads). Five different activity schedules were used for all five male subjects. These consisted of rest periods and periods of walking at different intensities. The present review will only review “Schedule II” because the authors acknowledged that in the other trials the cooling power was found to be insufficient to accommodate the metabolic rates whilst keeping the participants thermally comfortable. Schedule II was designed to compare the effect of changing the water inlet temperature at different activity levels. It consisted of two identical, repeated step changes: standing (rest), walking at 4.8 km/h, standing, walking again at 4.8 km/h and finally standing. During the first walking session, no adjustments in water inlet temperatures were permitted. During the second cycle, however, water temperatures were adjusted by the participants themselves at each body region to elicit thermal comfort.
The water temperatures needed for thermal comfort are shown in Figure 1.8. It can be seen that, during the initial standing session, most of the subjects preferred an almost uniform temperature over the entire body. This situation obviously did not change during the first walking session where no additional cooling was permitted. Immediately following the first walking session the restriction on additional cooling was removed; a decrease in most water inlet temperatures was requested by all subjects. The average changes requested were 1.2 to 1.3°C for the arms and thighs, and 0.2 to 0.6°C for the head and upper and lower torso. The greatest decrease in water temperature was requested for the lower legs (2.3°C). During the second walking session at 4.8 km/h, the request for decreases in water temperature ranged from 1.4°C for the head to 4.7°C for the lower legs. During the last standing period, the requested changes in water temperature were such that they essentially reproduced the situation that prevailed during the second standing session with only minor differences.

These results showed that body segment with the working muscles (thighs and calves) exhibited the highest variability in water temperatures, suggesting that muscles temperature may play a role in the preferred skin temperature, or that in order to achieve the same $T_{sk}$, one needs to cool more to compensate for heat
coming radially from the working muscle. Furthermore, while the changes in water temperatures to the head were the smallest, they were also on average starting from the lowest temperature level. Thus, maintaining the head at a relatively low temperature seems to have a profound effect on thermal comfort. Shitzer’s results strongly suggest that a comfortable $T_{sk}$ will vary according to body site and metabolic rate. However it is difficult to judge to what extent these differ, as no $T_{sk}$ was provided in this study. Since the suit water temperature and $T_{sk}$ may not necessarily be fully correlated due to a probably non-uniform tightness of the suit across the body, it is difficult to judge to what extent comfortable $T_{sk}$ varies between regions and between rest and exercise.

Shitzer (1973) analysed the water temperatures needed in a water-perfused suit to elicit thermal comfort at rest and during to exercise. Their study focused on water temperatures and not skin temperature. To the knowledge of the author, no study has directly investigated the effects of exercise on thermal sensitivity to cold with a method of intensity rating. The second main aim of the present thesis was therefore to investigate thermal sensitivity to cold at rest and during exercise at different body segments.

1.5. Thesis aims

In conclusion to this review, three major gaps currently remain in the literature related to thermal sensitivity to cold. These will constitute the main research questions of this thesis, which are:

1) Does thermal sensitivity to cold vary between whole body segments across the body?

As explained earlier in this chapter, several studies have already approached this question; however, none has systematically analysed responses starting from a
neutral and comfortable state. The following body segments will be analysed: chest, abdomen, upper- and lower back, upper- and lower arms, upper- and lower legs.

2) Are there differences in thermal sensitivity to cold within these body segments?

Several previous studies have measured thermal sensitivity at only one specific point within each segment, without considering whether this was representative of the whole segment. It will therefore be of great interest to compare central and lateral sites of each segment within the trunk, as well as anterior and posterior body sites on the limbs.

3) What are the effects of exercise on thermal sensitivity to cold measured by an intensity rating method?

Within this general question, several sub-questions will be covered, including the effects of exercise on both thermal sensation and thermal comfort during skin cooling, as well as the distribution across the body of any changes resulting from exercise.

As well as these three main research questions, two additional objectives will be covered in this thesis. These were part of one Bachelor degree and one Master degree research project. The author designed the experiments, assisted in the supervision, and analysed the raw data independently for inclusion in this thesis. These two additional studies provide an answer to two additional research questions:

4) Is there an effect of gender on thermal sensitivity to cold?

5) Is there an effect of ethnicity on thermal sensitivity to cold?
1.6. Rationale and approach

Results of the present research project will be used by the co-funding company, in order to improve clothing design for an optimisation of thermal comfort. Most current garments available at Decathlon have one unique level of insulation throughout, despite the common knowledge that thermal sensitivity is not uniform across the body. The general idea behind the present research is to adapt regional levels of clothing insulation according to local sensitivities to cold. Another main potential application of the current work is the inclusion of vents positioned according to thermal sensitivity, either for avoidance of cold and uncomfortable perceptions or to the contrary, for strongest cooling sensations. Moreover, results of this project may also be used for the improvement of a physiological model used in conjunction with a thermal manikin to predict thermal comfort in different conditions. Finally, research questions 4 and 5 will provide comparisons between members of different ethnic groups as well as between genders. These may be used to provide individual-specific the potential applications mentioned above.

Two general approaches will be used to answer the research questions posed in this thesis. Firstly, regional thermal sensitivity will be investigated with a water-perfused suit (WPS) which allows the cooling of whole body segments. Comparisons will be made between periods of rest and exercise. Secondly, comparisons will be made between locations within body segments (e.g.: lateral and central abdomen), thereby providing detailed body maps of thermal sensitivity to cold. This will be done with a 25 cm² thermal stimulus applied directly on the skin. This method will be used for rest and exercise comparisons, as well as gender and ethnicity comparisons.
Chapter 2

Study 1: Thermal sensitivity to cold at whole body-segments – Pilot study

2.1. Chapter summary

A study investigating the effects of whole body segments cooling was conducted at rest and during exercise. Using 5°C water running through a high density water-perfused suit, each of the 8 tested regions was individually cooled for 9 min, and then re-warmed for 3 minutes. Local and overall thermal sensations (LS and OS), as well as overall thermal comfort (OC), were reported by the participants every 3 minutes throughout the test. This protocol was repeated while sitting and while cycling at 30% of participants’ predicted maximal oxygen consumption (VO₂ max). The data was converted into the change in subjective data per change in skin temperature (T_sk), and the analysis revealed that ΔLS/ΔT_sk, ΔOS/ΔT_sk and ΔOC/ΔT_sk were greatly influenced by variations between segments in total ΔT_sk achieved, which rendered the data interpretation difficult. The present study was therefore used as a pilot study, which was necessary in order to improve the equipment and the testing protocol.

2.2. Introduction

A large body of literature is available regarding regional differences in sensory and regulatory functions of the human thermoregulatory system such as skin temperature (Clark et al., 1977), thermal comfort (Nakamura et al., 2008), thermal sensory spots (Strughold and Porz, 1931), thermal thresholds (Lee et al., 2010a) and cold sensitivity (Stevens, 1979). While these studies were performed with the sole purpose of expanding the scientific knowledge in this domain, researchers have also
recently explored regional differences in physiological factors with specific industrial applications in mind. This includes the work by Zhang (2003) on thermal sensation and comfort in uniform and non-uniform environmental conditions, with applications in the domain of vehicle climate control design. Similarly, Havenith and colleagues (Havenith et al., 2008; Smith and Havenith, 2011) investigated the regional distribution of sweat production, creating a dataset directly applicable by the textile industry. In both cases, the data can also be used in the context of thermal manikins, as well as for the development of physiological models of thermoregulation. The present research was done in a similar context, in an attempt to create a dataset of skin temperature ($T_{sk}$), thermal sensation and thermal comfort during the cooling of individual whole body segments, at rest and during exercise.

As presented in chapter 1, the regional distribution of thermal sensitivity to cold has been investigated in previous research. The work of Zhang and colleagues (e.g. Arens et al., 2006) proposes a predictive model of thermal sensation and thermal comfort. This was based on experimental tests involving cooling in warm environmental conditions or to the opposite, warming in cool conditions. Similarly, Cotter (1997) cooled different body segments while clamping the rest of the body at a warm temperature. Moreover, cooling patches of a unique size were used in their research which renders their data not applicable for whole body segments thermal comfort predictions. To the best of the author’s knowledge, no previous study has investigated thermal sensitivity of whole body segments in neutral thermal conditions. The first aim of the present study was therefore to compare thermal sensitivity to cold at whole body segments while ensuring that thermal sensation is neutral at the onset of cooling.

Furthermore, while skin cooling during exercise has been previously used in an experimental setting (e.g.: Price & Mather, 2004), limited information is known on how an individual’s thermal sensitivity to cold compares between periods of rest and exercise. Kemppainen et al. (1985) showed a change in thermal thresholds as a result of cycling, suggesting that thermal sensitivity measured during skin cooling may also be affected by exercise. Additionally, previous research has investigated
the alliesthesial effects of exercise and showed that a cold stimulation is perceived as less unpleasant when an individual is exercising, compared to rest (Attia & Engel, 1982). However the stimulus used was only 3.8 cm² in surface, and it is unclear whether this effect of exercise on thermal comfort also applies when a whole body segment is cooled. Therefore, the second purpose of this study was to compare both thermal sensation and thermal comfort between a resting and an exercising condition.

The results of this study are expected to be used in the context of sports clothing, with applications in mind such as the regional distribution of insulations levels or the strategic placement of air vents within clothing in order to optimise wearer comfort.

2.3. Methods

2.3.1. Participants

The study was advertised at Loughborough University via group emails and posters displayed around campus. The inclusion criterion were: being male, European (Caucasian), aged 18-30 years, and at least recreationally active, defined for the purpose of this study as performing physical activity for at least 2 hours per week. The age range was chosen due to the potential age effect on thermal sensitivity to cold (for a review see Guergova & Dufour, 2011), and the fitness level criterion was used to ensure that all participants were able to complete the test with no difficulties.

Twelve healthy male participants aged 21.9 ± 2.5 years were recruited from the student population. They were sent a participant information sheet (Appendix 1) via email, giving a description of the tests, and asking to refrain from high intensity exercise and alcohol 24hours prior to testing. They were also requested to abstain
from caffeine and food consumption during the 2 hours prior to each session. Each participant was asked to come to the laboratory on 4 occasions (1 pre-session and 3 experimental sessions), with at least two days between each test.

2.3.2. Pre-experimental test session

All participants were required to attend the Environmental Ergonomics Research Centre at least two days prior to the first experimental session. The pre-experimental session consisted of a series of anthropometric measurements, followed by a sub-maximal fitness test. Upon arrival at the laboratory, participants were given a detailed explanation on the testing procedures. They then completed a health questionnaire and provided informed consent (Appendix 2). At the end of the session, the participants were familiarised with the procedure and thermal sensation scales used in the experimental sessions.

2.3.2.1. Anthropometric measurements

Stature and mass were first measured, respectively with a stadiometer (Seca, Hamburg, Germany; resolution= 0.5 cm) and a Mettler ID1 Multirange electronic scale (Mettler Toledo, Leicester, UK; resolution= 1g). Skinfold thicknesses were measured using Harpenden Calipers (British Indicators Ltd, St Albans, UK; resolution = 0.2 mm) at the following sites: pectoral, triceps, biceps, abdominal, mid-axillary, supra-iliac, sub-scapular, mid-thigh and calf. The skinfold measurements were done according to Eston and Reilly (2005). In order to calculate percentage body fat (%BF), body density was first determined using Jackson and Pollock’s equations (1978):

\[
\text{Body density} = 1.112 - (0.00043499 \times \sum T) + (0.00000055 \times (\sum T)^2) - (0.00028826 \times \text{age})
\]
where $\sum 7 = \text{sum of 7 skinfolds in mm: pectoral, mid-axilla, abdomen, suprailiac, subscapular, triceps, mid-thigh.}$

%BF was then calculated using Siri's equation (1956):

$$\text{% BF} = \left\{ \frac{4.95}{\text{body density}} - 4.5 \right\} \times 100$$

The methods used for %BF are reliable and valid when compared with hydrostatic weighing (Greene et al, 1998).

### 2.3.2.2. Sub-maximal fitness test

Maximum oxygen consumption ($\text{VO}_{2\text{ max}}$) was estimated during the second part of the pre-experimental session, using a modified version of the Åstrand-Rhyming sub-maximal cycling test (Åstrand and Rhyming, 1954). Participants were fitted with a Polar heart rate monitor and watch (Polar Electro Oy, Kempele, Finland). They then entered the laboratory ($T_a = 21^\circ\text{C}; \text{Rh} = 40\%$) while wearing a T-shirt, shorts and trainers. Room ambient temperature and relative humidity were measured using a Vaisala HMP35DGT sensor (Vaisala, Helsinki, Finland) and recorded at 1 minute intervals using an Eltek/Grant 10 bit, 1000 series squirrel data logger (Grant Instruments, Cambridge, England).

The test consisted of continuously cycling for 20 minutes at 60 rpm on an electromagnetically braked cycle ergometer (Lode Excalibur, Groningen, The Netherlands). The initial workload was set at 100W and was increased by 30W at 5, 10, and 15 min. Similarly to the Åstrand-Rhyming single stage test, initial workload was adjusted to ensure an initial HR of between 100 and 120 bpm. If HR was below 100bpm or above 120bpm after 2 minutes of exercise, workload was respectively increased or decreased by 20W. This was repeated until the HR fell within the target zone of 100 to 120 bpm. Heart rate was recorded at the end of each stage and plotted against the corresponding workload, and a linear trendline was drawn up to the value of age predicted maximal heart rate ($220 - \text{age}$), using Microsoft
Office Excel 2007. This allowed maximal workload to be predicted from the x-axis. Then, estimated $\text{VO}_2\text{max}$ was calculated from the ACSM metabolic equation for cycling (Franklin et al., 2000).

$$\text{VO}_2\text{max} = 7 + (10.8 * \frac{\text{Maximal power}}{\text{body mass}})$$

Where maximal power is the maximal workload calculated from the graph.

At the end of the fitness test, participants were offered to cool down if required. They were then given a detailed description of the procedures which would be used in the following sessions, and around 10 minutes were spent in practicing to rate their local and overall thermal sensations (LS and OS) and their overall thermal comfort (OC).

### 2.3.3. Experimental sessions

The laboratory methods for all experiments undertaken are described under a generic experimental protocol which was approved by Loughborough University ethical committee (Generic Protocol G10-P3). Participants were tested under 2 different conditions: rest and exercise. Because of the duration of the tests, the exercise condition was split into 2 tests. This was done to ensure that the results are not affected by fatigue. The 3 experimental tests (rest, exercise 1 and exercise 2) were spaced by at least 48 hours and the order of the sessions was balanced.

#### 2.3.3.1. Equipment and experimental set-up

Skin cooling was achieved with the use of a bespoke two-piece high density water-perfused suit (WPS; Med-Eng Systems Inc., Pembroke, Canada) consisting of 2.5 mm internal diameter medical grade PVC tubing, sewn in a shirt and a pair of trousers. The tubing covered the following body segments: chest, abdomen, upper arms,
lower arms, upper back and lower back. The trousers consisted of the buttocks, front and back upper legs, and lower legs. Water perfused suits operate on the principle of conduction, by allowing heat transfer between the cold water and the warmer skin (or vice-versa). The temperature gradient is widened and the cooling potential is increased by lowering the inlet temperature of the liquid. Similarly, higher water flow rates increase the rate of heat transfer and thereby help to maximise cooling by conduction (Speckman et al, 1987).

Due to the complex tubing design of each body segment (e.g. different tube lengths, different number and radii of the bends), the maximal flow differs at each body part due to different resistances. In the present study, the aim was to investigate the relationship between skin temperature and thermal sensation/comfort at rest and during exercise. The flow was therefore always kept at its maximal possible value for each zone, which allows maximum skin cooling at each segment while having a fair comparison between rest and exercise. The WPS was connected to a cooling system. This cooling system had initially been designed for a different research project, but substantially modified in the context of the present project. This cooling system consisted of the following main components: 1 industrial chiller (Tae Evo M10, ICS Temperature Control, Southampton, UK), 2 temperature-controlled water baths (TLC 15 and TLC 30, Tamson Instruments, Zoetermeer, Netherlands), 2 powered water pumps (NP 85, Salamander Pumps, Bedford, UK), 2 heat exchangers (15-17 plate-type, Bowman, Birmingham, UK), and one custom-built “switchboard”. The industrial chiller is used together with the heat exchangers to aid the water baths in keeping a low water temperature. The water leaves each water bath via the pump, goes through the switch board, and exits the board via connectors onto the WPS. The water then exits the suit, goes through the switch board again after which it reaches the heat exchanger where it is cooled back down before re-gaining its initial position in the water bath. For re-warming, a water boiler is used together with its separate powered pump. The cooling system design is depicted in Figure 2.1. The specificity of this cooling system compared with others is the fast water circulation in the main pipes, out of which the water is used in the WPS. This is made possible by using 3 independently powered water pumps, each of which
inducing a flow of 8 litre per minute. Most other cooling systems use the water bath pump, which has a flow of around 2 litres per minute (e.g. Cotter, 1997), to supply whole body segments and sometimes the whole body. As explained above, using a greater water flow allows a greater rate of heat transfer between water and the skin, which ultimately results in greater $T_{sk}$ changes for a given amount of time.

![Diagram of cooling system](image)

**Figure 2.1.** Cooling system used to cool down individual body segments

The thermal sensation scale used was the ISO 11-point thermal sensation scale (ISO 10551) ranging from extremely cold (-5) to extremely hot (+5) with a value of 0 corresponding to a neutral thermal sensation. Researchers (e.g. Golja & Mekjavić, 2005) often use a unipolar scale for thermal comfort, ranging between “comfortable” (+1) and very uncomfortable (-4). In the present study however,
“positive” thermal comfort was expected according to the principle of alliesthesia\(^1\). Indeed, local cooling and rewarming of participants’ body segments, as well as the cooling during periods of exercise, have both been shown to trigger positive thermal comfort (Arens et al., 2006) or thermal pleasantness (Attia and Engel, 1982), respectively. The thermal comfort scale used was therefore modified from Arens et al. (2006), ranging from between -5 (very uncomfortable) and +5 (very comfortable).

2.3.3.2. Participants’ preparation

The order of the 3 experimental sessions was balanced across participants to prevent any potential order effect. Upon arrival, participants were given a description of the experimental session and changed into their own shorts. Following careful instruction, each participant inserted a rectal thermometer (Grant Instruments, Cambridge, England) with a plastic bead 10 cm beyond the rectal sphincter for measurement of core temperature (\(T_c\)) during the experiment. For measurement of \(T_{sk}\) during cooling and rewarming, one skin thermistor (Grant Instruments, Cambridge, England) was attached to each of the following testing body segments: chest, abdomen, upper arm, lower arm, upper back, lower back, thigh and calf. The thermistors were placed on each body segment according to the locations described by Choi et al. (1997): chest, abdomen, scapular, lumbar, posterior upper arm, anterior forearm, anterior thigh, anterior calf. Skin and rectal temperature sensors were connected to an Eltek/Grant 10 bit, 1000 Series data logger (Grant Instruments, Cambridge, England) recording temperature at 2 second-intervals. This frequency was chosen because of the quick skin temperature changes expected in this study. Participants were fitted with a Polar heart rate monitor and watch (Polar Electro Oy, Kempele, Finland). They were then dressed in a one piece Lycra leotard (worn over briefs, skin thermistors and heart rate monitor). Wires exited the leotard by the neck. The leotard fabric is thin and

\(^1\) Alliesthesia is defined as the pleasure/displeasure sensation aroused by a given peripheral thermal stimulus according to the internal state of an individual.
elastic, fits skin closely and prevents movement of the thermistors attached to the skin. It has been previously reported that lycra material provides an ideal insulation level for skin cooling experiments, by being thick enough to ensure that thermistors are not influenced by the water running through the WPS (Zhang, 2003). While inevitably preventing the maximal cooling capacity of the WPS by providing insulation to the skin, lycra leotards have the advantage of making skin temperature more uniform during local skin cooling (Zhang, 2003).

2.3.3.3. Experimental procedure

Participants entered the testing laboratory and donned the two-piece custom-made high density Cool Tubesuit™ (Med-Eng Systems Inc., Canada) consisting of full length trousers and a long sleeved top worn over the leotard (the latter was worn for hygiene reasons). This WPS included the following individually controlled body zones: chest, abdomen, upper back, lower back, upper arms, forearms, thighs, calves. The WPS was composed of spandex mesh fabric, and each body zone had tygon tubing sewn underneath the garment. The total tubing length and surface area of each zone are shown in Table 2.1.

Table 2.1 Tubing lengths and zones’ surface areas for water-perfusion suit

<table>
<thead>
<tr>
<th>Zone</th>
<th>Upper back</th>
<th>Chest</th>
<th>Lower back</th>
<th>Abdomen</th>
<th>Lower arms</th>
<th>Upper arms</th>
<th>Front thighs</th>
<th>Rear thigh</th>
<th>Lower leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Length (m)</td>
<td>8.3</td>
<td>8.3</td>
<td>9</td>
<td>9</td>
<td>3.8*2 = 7.2</td>
<td>6.4*2 = 2.8</td>
<td>7.5*2 = 15</td>
<td>5.3*2 = 10.6</td>
<td>4.7*2 = 9.2</td>
</tr>
<tr>
<td>Surface area (m²)</td>
<td>0.12</td>
<td>0.12</td>
<td>0.11</td>
<td>0.11</td>
<td>0.05*2 = 0.10</td>
<td>0.08*2 = 0.16</td>
<td>0.11*2 = 0.22</td>
<td>0.06*2 = 0.12</td>
<td>0.09*2 = 0.18</td>
</tr>
</tbody>
</table>
To promote maximum heat transfer between the skin and the garment, a two piece bespoke compression tracksuit was worn over the cooling garment which was available in small, medium and large. The upper-body part of this garment had two extra zips going from the armpit to the hip area (one on each side). A lace was also incorporated across the zips to allow an adjustment of the tightness. The lower-body part of the garment simply had a zip on each side going from the hip region to the ankles. This garment had two purposes. It was first used in an attempt to improve the distribution of the suit’s tightness onto the skin over the whole body. Indeed, preliminary tests highlighted the fact that the WPS was tighter in certain areas than others, resulting in a non-uniform heat transfer over different areas of the body. The second purpose of the covering garment was to minimise heat transfers between the cold water running through the suit and the warmer air temperature of the laboratory. Participants then put their shoes on and either sat on the cycle ergometer (exercise) or on a stool (rest), depending on the condition.

**Resting condition**

Participants sat down on a stool adjusted in height so that they could comfortably touch the floor with both feet. At that stage the suit was connected to the cooling system. Three water temperatures were available in the switchboard: 28°C (neutral), 5°C (cooling) and 35°C (rewarming). In the resting condition all 8 body segments were initially connected to the neutral water bath set at 28°C. This temperature was selected according to subjective ratings measured during experimental pilot tests. The purpose was to reach overall thermal comfort and overall thermal neutrality after 10 min of rest with water being perfused through the whole suit. The water pump was switched on, which will be referred thereafter as t = 0 min. All zones remained connected to the neutral bath between t = 0 min to t = 10 min. The purpose of this period was to stabilise $T_{sk}$ and $T_c$. Heart rate, local thermal sensations, overall thermal sensation and overall thermal comfort were recorded at times t = 5 min and t = 10 min. Participants reported their local thermal sensation at 8 body segments in the following order: chest, abdomen, upper back,
lower back, upper arm, lower arm, upper legs, and lower legs. All the measurements took around 1 minute in total. The order of local sensations recordings was not balanced to avoid differences in time intervals between sensation measurements.

At \( t = 10 \text{ min} \), the first tested body zone was switched to the cold bath set at 5°C and its pump was switched on, while the other zones remained connected to the 28°C water bath. From then on, heart rate and all thermal sensation and comfort values were recorded every 3 minutes for 9 minutes. At \( t = 19 \text{ min} \), the tested zone was connected onto the water heater, in which the water was set at 35°C. This temperature had been chosen from the pilot experiments which showed that rewarming a zone for 3 minutes at 35°C was enough to re-establish the initial skin temperature, although it was anticipated that different body parts would cool down and rewarm at different rates. If the participant still perceived the segment as cool or cold, the rewarming period was prolonged until thermal neutrality. At the end of the rewarming, the zone was reconnected onto the 28°C bath and the next tested zone was switched onto the 5°C bath, simultaneously. The 9 minutes cooling – 3 minutes re-warming process was repeated for each body zone (chest, abdomen, upper back, lower back, arms, upper legs and lower legs) in a balanced order. An example of the procedure sequence is illustrated in Figure 2.2.

Figure 2.2. Sequence of segmental cooling and rewarming during the procedure at rest
**Exercise condition**

A stabilisation period of 20 minutes was used in the exercise condition, during which participants cycled at 60rpm with a resistance equivalent to 30% VO\textsubscript{2max}. This duration was selected according to pilot tests suggesting that this was the time needed to reach a plateau in T\textsubscript{c} whilst cycling at that particular relative intensity. Participants continued cycling at the same intensity throughout the exercise condition. Pilot experiments also highlighted that cooled skin temperatures would be regained too quickly with the 35°C water, with the potential risk of quickly reaching the other side of the thermal sensation scale (i.e. warm/hot thermal sensations). As a result, the duration of the rewarming was kept at 3 minutes but the neutral 28°C water as used in rest of the body segments was used instead of 35°C. An example of the procedure sequence is illustrated in Figure 2.3.

![Figure 2.3. Sequence of segmental cooling and rewarming during the procedure during exercise](image)

**2.3.4. Data analysis**

To understand the data better, the evolution of skin temperature, local thermal sensation, overall thermal sensation and overall thermal comfort were plotted against time in line graphs. Each condition is presented on a separate graph, and
each line within a graph represents the cooling of one body segment. Next, the
following relative values were calculated at time = 9 (end of cooling) and plotted on
bar charts (one bar per body segment): $\Delta T_{sk}$, $\Delta$ Local thermal sensation,
$\frac{\Delta \text{Local sensation}}{\Delta T_{sk}}$, $\frac{\Delta \text{Overall sensation}}{\Delta T_{sk}}$ and $\frac{\Delta \text{Overall comfort}}{\Delta T_{sk}}$

After visual inspection of the graphs, a statistical analysis was deemed not
necessary because of uncertainties regarding the reliability of the data. This will be
explained in the discussion.

2.4. Results

2.4.1. Participants characteristics

Age, body fat percentage and predicted maximal oxygen consumption for the 12
participants are listed in Table 2.1.

<table>
<thead>
<tr>
<th></th>
<th>Age (years)</th>
<th>BF %</th>
<th>Predicted VO$_2$ max (ml · kg · min$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>21.9</td>
<td>8</td>
<td>49.6</td>
</tr>
<tr>
<td>SD</td>
<td>2.5</td>
<td>2.7</td>
<td>7.2</td>
</tr>
</tbody>
</table>

2.4.2. Core temperature

As depicted in Figure 2.4, core temperature constantly decreased during the resting
session, with an average drop of 0.48 ± 0.13°C ($p < 0.01$) from start to finish.
During exercise, core temperature increased by an average of $0.38 \pm 0.13^\circ C$ during the 20 min warm up ($p < 0.01$), but did not significantly change between the end of the warm-up and the end of the session ($p > 0.05$). Mean core temperature between the end of the warm up and the end of the test is depicted in Figure 2.5.
2.4.3. Skin temperature

Figure 2.6  REST: Evolution of Tsk at each body segment during cooling (0-9min) and rewarming (9-12min)

Figure 2.7  EXERCISE: Evolution of Tsk at each body segment during cooling (0-9min) and rewarming (9-12min)
2.4.4. Local thermal sensations

Figure 2.8  REST: Evolution of the local thermal sensation at the treated body segment

Figure 2.9  EXERCISE: Evolution of the local thermal sensation at the treated body segment
2.4.5. Overall thermal sensation

Figure 2.10 REST: Overall thermal sensation during the cooling of each body segment

Figure 2.11 EXERCISE: Overall thermal sensation during the cooling of each body segment
2.4.6. Overall thermal comfort

Figure 2.12 REST: Overall thermal comfort during the cooling of each body segment

Figure 2.13 EXERCISE: Overall thermal comfort during the cooling of each body segment
2.4.7. Bar charts of relative values

Figure 2.14  Change in Tsk observed between \( t = 0 \) and \( t = 9 \) min

Figure 2.15  Change in local thermal sensation between \( t = 0 \) and \( t = 9 \) min
Figure 2.16 Change in local thermal sensation over change in Tsk at the cooled segment between t=0 and t=9

Figure 2.17 Change in overall thermal sensation over change in Tsk at the cooled segment between t=0 & t=9
2.5. Discussion

The first aim of the current study was to compare thermal sensitivity to cold at 8 different body segments, and the second aim consisted of comparing the effects of regional cooling at rest and during exercise. In the present study, 3 definitions of thermal sensitivity were considered:

1) Change in local thermal sensation per change in local $T_{sk}$ at the cooled segment
2) Change in overall thermal sensation per change in local $T_{sk}$ at the cooled segment
3) Change in overall thermal comfort per change in local $T_{sk}$ at the cooled segment

Figure 2.18 Change in overall thermal comfort over change in $T_{sk}$ between $t = 0$ and $t = 9$ min. A negative value means that the cooling resulted in an improvement in overall thermal comfort.
The first point to consider is core temperature. As described in 2.4.2, $T_c$ significantly decreased throughout the resting session, despite rewarming the skin after each cooling period. This suggests that thermal sensation and thermal comfort may have been influenced by this change in $T_c$ throughout the test. The rationale behind the protocol was to start each cooling period from the same (neutral) state, physiologically and perceptually. The decrease in core temperature in the resting condition must be acknowledged as a limitation.

Regarding $T_{sk}$, the use of one unique “clamping” water temperature on each targeted body segment during the stabilisation period did not result in a return to the same pre-cooling skin temperatures (Figure 2.7 and Figure 2.8). In terms of local and overall thermal sensations however, an initial value in the vicinity of thermal neutrality was found for all body segments at $t = 0$ (end of stabilisation period) in the resting condition (Figure 2.9 and Figure 2.11). In contrast, the initial local thermal sensation in the exercise condition ranged between $+1$ (“slightly warm”) and $+3$ (“hot”) before starting the cooling period, while the overall thermal sensation was above $+2$ (“warm”) in all experiments (Figure 2.10 and Figure 2.12). Similarly, overall thermal comfort at $t = 0$ was between $+2$ and $+3$ (“comfortable”) for all body segments at rest, while it showed negative values below $-1$ (“Just uncomfortable”) in the exercise condition.

In the present study, an attempt was made to use $T_{sk}$ as the “clamped” parameter. This should have allowed a direct comparison of thermal sensitivity between segments and between conditions by observing differences in thermal sensation and comfort. This was however not successful due to a poor efficiency of the WPS at controlling $T_{sk}$ which may be caused to its loose fitting. This resulted in differences between body segments and between conditions in pre-cooling $T_{sk}$ as well as in thermal sensations and thermal comfort. Furthermore, the same clamping temperature for both conditions means that at rest, the cold thermal stimulus is a thermal stress, going away from thermal neutrality and thermal comfort, whereas in the exercise condition the thermal stimulus relieved participants from the initial (hot) thermal stress, bringing them back towards thermal neutrality and thermal comfort (Figure 2.14). Reflecting on the decisions
made regarding the protocol, this limitation could have been avoided by using thermal sensation as the “clamped” parameter instead of $T_{sk}$. This could have been achieved with ad libitum adjustments of the water temperature by each participant until local thermal sensation at the targeted segment reached neutrality. Although this would have certainly increased the duration of the experiments and the number of testing sessions (to avoid fatigue in the exercising condition), this approach would have allowed a better comparison between rest and exercise as well as between body segments.

The next observation is the lack of efficacy of the WPS at reducing $T_{sk}$ by the same amount ($\Delta$) at each body segment during the cooling period. As shown on Figure 2.15, $\Delta T_{sk}$ greatly varied between body segments. For example, a decrease of around 6.5°C was found at the upper legs but of only 1.5°C at the lower legs in the resting condition. These variations between segments were not expected and create difficulties in the interpretation of the data. Indeed, thermal sensitivity being defined as a change in thermal sensation (or comfort) for a given change in $T_{sk}$ means that a low change in $T_{sk}$ is more likely to be interpreted as a segment of high sensitivity. However, the relationship between $T_{sk}$ and thermal sensation is not a constant and may be steeper in the initial change from thermal neutrality. This means that unless the total $\Delta T_{sk}$ is similar between zones, this may affect the interpretation of thermal sensitivity, as $\Delta$ local thermal sensation divided by a small $\Delta T_{sk}$ will be more likely to be a large number. Sticking to the example of the lower legs at rest, a $\Delta T_{sk}$ of 1.5°C resulted in a $\Delta$ local thermal sensation of 2 units; however it is possible and quite likely that a further decrease of 1.5°C in $T_{sk}$ would have resulted in a decrease in sensation of less than 2 units. Using the current data in an attempt to compare thermal sensitivities at each body segment leads to unexpected conclusions. Specifically, as highlighted in Figure 2.17, the $\Delta$ local thermal sensation over $\Delta T_{sk}$ value is highest for the lower legs, while the absolute sensation at this segment only dropped to -2 (“cool”) after 9 minutes of cooling.

Regarding the reasons behind these fluctuations in $\Delta T_{sk}$ between segments, several possibilities exist. Firstly, the WPS design, and more specifically the tubing density, is not equal at each body segment (Table 2.1). In order to provide the same cooling
power at each body segment, the same length of tube per surface area would have been needed. Secondly, despite the high water-flow used in the present study, each body segment can only be perfused by a certain maximal flow, due to different resistance levels on each body segment. Since resistances are not equal at all body segments, the maximal flow and therefore the maximal cooling power will inevitably differ between body segments. Furthermore, despite the tight-fitting garment worn on top of the WPS, the tightness of the WPS was not uniform across the body. For example, the abdomen fitted tightly onto most participants, whereas the chest was quite loose (i.e. further away from the skin). This resulted in a total $\Delta T_{sk}$ of 6°C at the abdomen but only 3.5°C at the chest, while these two segments have almost the same tubing density and pattern. The same issue exists for participants of different body size and shape; those who are thinner are less likely to have a good contact between their skin and the WPS. Another factor which may explain the differences $\Delta T_{sk}$ between body segments is physiology-related. Indeed, it is well established that different areas of the body lose their heat content more readily than others. For example, Nakamura et al. (2008) found that applying the same cold stimulus at different areas of the skin resulted in different levels of $\Delta T_{sk}$ and suggested that these regional differences in heat loss are likely caused by differences in skin blood flow due to vasomotor status and tissue vascularity. Moreover, Li and colleagues (2005) found that the lateral chest and lateral abdomen are subjected to the greatest $\Delta T_{sk}$ rates when individually exposed to a 20°C ambient air temperature while the rest of the body is covered. Although the present water stimulus is much more dominant in defining the $T_{sk}$ drop than Li and colleagues’ air exposure, differences in $\Delta T_{sk}$ may be partially due to the body’s natural regional differences in heat loss. The limitations related to regional differences in $\Delta T_{sk}$ are almost unavoidable for any study using a WPS or water-perfused patches (e.g.: Cotter, 1997; Nakamura et al., 2008).

Additionally, these differences may have appeared worse than the reality due to a potential issue related to $T_{sk}$ measurement. Indeed, the use of only one thermistor per body segment may not have been enough, as $T_{sk}$ may vary within the cooled body segment. Because of the tubing pattern, it is even possible that the
thermistor falls under an “uncooled” region of the WPS, resulting in a systematic error in $T_{sk}$. Looking at the data and the very low $\Delta T_{sk}$ found at the lower leg, it is possible, if not likely, that the positioning of the thermistor on that particular segment may have been in an area not covered by the WPS tubes, resulting in a systematic measurement error. The outcome of this major limitation is that important doubts exist in the reliability and validity of the $T_{sk}$ measurements taken.

As a result of these important limitations, a statistical data analysis was not performed with the present data, and it seemed illogical to compare the present results with previous research whilst having such doubts about the validity of the data. Consequently, attention was given to ways in which to overcome the limitations listed above, in order to answer the same empirical questions appropriately.

2.5.1. Conclusions

The present study may be considered as a pilot study which helped to highlight a series of limitations to the present technique, and improvements which will need to be made in order to overcome these limitations. These listed below.

1. $T_c$, as well as thermal sensation and comfort, must be at the same (neutral) level before the start of each cooling in order to have a fair comparison between body segments. If the same protocol is used again, the re-warming period will need to be longer, in order to avoid a decrease in $T_c$ throughout the test in the resting condition.

2. The WPS is not currently capable of clamping $T_{sk}$. As a consequence, setting the water at a fixed temperature for all body sites does not mean that each segment will have an equal $T_{sk}$. The protocol needs to be adjusted in order to reach a neutral $T_{sk}$ and/or thermal sensation before the cooling starts. This could be achieved by allowing participants to make ad libitum changes to the water temperature until they reach thermal neutrality.
3. Similarly, the suit does not seem to cool each body segment to the same degree despite using the same cold water temperature. This is likely to be due to a different tube density between zones and more importantly to a poor conductance at some areas due to the garment being loose. Changes will need to be made to the WPS in order to make it more “tight-fitting” at all body segments.

4. One thermistor per targeted segment is not sufficient for the measurement of $T_{sk}$. Several $T_{sk}$ measurement points will therefore need to be used on the cooled body segment.
Chapter 3

Study 2: Thermal sensitivity to cold at whole body segments during periods of rest, exercise and recovery

3.1. Chapter summary

This study aims to investigate the distribution of thermal sensitivity to cold at whole body segments during periods of rest and exercise, while taking into account the limitations highlighted in study 1. Using a customised liquid cooling garment, individual body segments were continuously cooled during three consecutive conditions: 30 min rest, 15 min exercise (cycling at 30% VO\textsubscript{2} max) and 15 min post-exercise recovery. Local and overall thermal sensation and thermal comfort were scored at 5 min intervals. Results showed that the lower back, upper arms and upper legs are the most sensitive body segments. In contrast, particularly low levels of thermal sensitivity were found at the abdomen and lower legs. Regarding the effects of condition, the results revealed a significant decrease in thermal sensitivity to cold during exercise and post-exercise recovery, compared with resting values. While confirming the alliesthesial effect of exercise on thermal comfort during cooling, the present results also show that the intensity of local cold sensations is significantly changed as a result of exercise.

3.2. Introduction

In study 1, an attempt was made to answer the following empirical questions:

- How do the different body segments compare in terms of thermal sensitivity to cold?
- How does exercise influence thermal sensitivity to cold?

Several limitations were highlighted, and the present chapter is the logical step following the conclusions drawn in chapter 2. Study 1 therefore permitted several improvements to both the equipment and the protocol used. Before describing the procedures used in the current study, the methodology section will first explain the changes made in response to the limitations highlighted in the previous chapter.

3.3. Methods

3.3.1. Equipment and protocol modifications

3.3.1.1. Water-perfused suit

One of the issues met was regarding the interpretation of the data caused by unequal drops in $T_{sk}$ at different body sites, despite water running through the suit being at the same temperature. It was therefore envisaged to use a different means of skin cooling than the water-perfused suit (WPS) described in chapter 2. An attempt was made to build cooling patches similar to those used by Nakamura et al. (2008). A prototype cooling patch was built with the help of research and development engineers at Oxylane (Appendix 3), but it soon became apparent that this job may be too ambitious and that patches were likely to come with their own limitations.

Consequently, it was decided that the best and most realistic option would be to invest time in the improvement of the WPS, for which the limitations were already well known. Two main changes were made to the garment. Firstly, the issue of tightness of the suit was solved by cutting through the sides of the top and trousers, and adding snap fasteners (“poppers”) along each side. Several rows of snap fasteners were incorporated, allowing the adjustment of the suit tightness according to the wearer’s body size. This would also reduce any “gap” present
between tubes, especially at the lower leg where this had been highlighted as a limitation. Examples of this improvement are illustrated in Figure 3.1 and 3.2.

![Figure 3.1 Snap fasteners incorporated on the sides of the WPS. The pictures shows the chest and abdomen](image)

In order to increase contact between the tubes and the skin, Velcro-type straps were used to surround each cooled body segment. This had both advantages of having the suit tighter against the skin and to insulate the water from the warmer environment. Two examples of these straps are shown on Figure 3.3 and 3.4.

![Figure 3.2 Rows of snap fasteners incorporated on the sides of the WPS. The pictures shows the forearm](image)
Figure 3.3 Velcro strap used around the upper arm

Figure 3.4 Velcro strap placed around the abdomen
Having a similar strap around the chest or the upper back was not possible, so another compression system was developed instead. This consisted of applying voluminous foam strapped onto the body segment under a shoulder support strap and a bespoke strap, as illustrated in Figure 3.5.

![Figure 3.5 Shoulder support Velcro strap (A), bespoke strap and foam (B) used to improve contact between the suit and the skin at the chest and upper back](image)
3.3.1.2. Equipment and protocol

Several pilot tests were performed, with two main issues to solve. Firstly, regarding measurements of $T_{sk}$, comparisons were made between thermistors, thermocouples and wireless iButtons. The outcome of these pilot tests was that despite being slightly slower at responding to temperature changes than the thermocouples and thermistors, iButtons have the advantage of being wide, making them less likely to fall under a non-cooled area or in-between 2 tubes. Their thickness is also an advantage because it reduces the effect of the tubes temperature on the $T_{sk}$ measurement. Furthermore, using wireless iButtons would allow the inclusion of several $T_{sk}$ measuring points without extra wires which can create issues such as tangling or pain when fitted under a tight “leotard” garment. In the present study, 4 wireless iButtons will be used per body segment, which should provide a good estimate of the cooled segment mean $T_{sk}$, as they have been suggested to be a valid alternative for human $T_{sk}$ measurement (Smith et al., 2009).

Secondly, different protocols were envisaged and pilot tested. As highlighted in study 1, the cooling of each segment should start from the same neutral level, both in terms of $T_c$ and thermal sensation and comfort. In order for this condition to be met, it was decided to test only one body segment per experimental condition, thereby avoiding a constant drop in $T_c$ despite rewarming the cooled segment.

Overall, the reflection and the pilot tests performed before the current study allowed the elaboration of a testing protocol which should overcome the limitations highlighted in chapter 2. This will be described in details in the next sections.

3.3.2. Participants

The study was advertised at Loughborough University via group emails and posters displayed around campus. The inclusion criteria were: being male, European (Caucasian), aged 18-30, being at least 1.75m tall, and recreationally active, defined for the purpose of this study as performing physical activity for at least 2 hours per
week. The age range was chosen due to the potential age effect on thermal sensitivity to cold (for a review see Guergova & Dufour, 2011). The criterion imposed on height was due to observations in the previous experiment and the pilot tests, that for shorter participants, some body segments of the WPS were not covering only the targeted body segment but also the segment adjacent (e.g.: part of the abdomen cooled when only the chest is perfused with cold water). The physical activity criterion was used to ensure that all participants were able to complete the test with no difficulties.

Eight healthy male participants aged 22.0 ± 3.5 years were recruited from the student population. They were sent a participant information sheet similar to that presented in Appendix 1 via email, giving a description of the tests, and asking to refrain from high intensity exercise and alcohol 24hours prior to each test. They were also requested to abstain from caffeine and food consumption during the 2 hours prior to each session. Each participant was asked to come to the laboratory on 11 occasions (1 pre-session and 10 experimental sessions), with at least 48hrs between each test.

3.3.3. Pre-experimental test session

All participants were required to attend the Environmental Ergonomics Research Centre at least two days prior to the first experimental session. Upon arrival at the laboratory, participants were given a detailed explanation on the testing procedures. They then completed a health questionnaire and provided informed consent (Appendix 2). The pre-experimental session consisted of a series of anthropometric measurements, followed by a sub-maximal fitness test. The procedure followed and the tests carried out were identical to those described in chapter 2. Briefly, this first consisted of anthropometric measurements of height, weight, and skinfold thicknesses. These were taken using the 7-point caliper method (Jackson and Pollock, 1978) specific to the male population for calculation of body fat percentage (BF %). Maximal oxygen consumption (VO₂ max) was then deduced using a modified version of the Åstrand-Rhyming sub-maximal cycling test
(1954), identical to that described in chapter 2. At the end of the session, the participants were familiarised with the procedure and thermal sensation scales used in the experimental sessions.

3.3.4. Experimental sessions

The laboratory methods for all experiments undertaken are described under a generic experimental protocol which was approved by Loughborough University ethical committee (Generic Protocol G10-P3). Each experimental session consisted of cooling a single body segment or combination of body segments. The following 8 single segments were tested: chest, abdomen, upper arms, lower arms, upper back, lower back, upper legs, and lower legs. In addition, 2 combinations of segments were also tested: front torso (chest + abdomen) and whole back (upper back + lower back). This was requested by the PhD co-funding body for their own analysis, and will therefore not be included in the present thesis. Participants were thus tested on 10 occasions in total. The order of the 10 experimental sessions was balanced across participants to prevent any potential order effect. Rest, exercise, and post-exercise recovery were tested in each session. For each participant, experimental sessions took place at the same time of the day and were spaced by at least 48 hours to avoid any effect of fatigue.

3.3.4.1. Equipment and experimental set-up

In the present study, the cooling system described in study 1 was used together with the improved WPS described in 3.3.1.1. The total tubing length and surface area of each zone can be found in Chapter 2 (Table 2.1). In order not to influence the room temperature due to the heat rejected by the industrial chiller, the short tubes linking the heat exchangers to the chiller were replaced with much longer hoses, which made it possible to place the chiller outside the laboratory during the experiments. Also, the laboratory used in the present study was a temperature-
and humidity-controlled climatic chamber perfectly able to keep a steady environmental condition despite the water baths and pumps heat rejection. The experimental set-up is illustrated in Figure 3.6.

![Figure 3.6 Experimental set-up in the climatic chamber](image)

**Legend:**

1 = computer on which the investigator recorded the subjective ratings reported and in which the water baths temperatures are recorded

2 & 4 = water bath

3 = Switch board of the cooling system

5 = Hose allowing the industrial chiller to be kept outside the climatic chamber

6 = Thermal sensation and thermal comfort scales

Regarding scales, thermal sensation was reported on a modified version of the ISO 11-point thermal sensation scale (ISO 10551) ranging from extremely cold (-10) to extremely hot (+10) with a value of 0 corresponding to a neutral thermal sensation. In the present study, positive comfort values were possible according to the principle of alliesthesia. The thermal comfort scale used was therefore modified from Arens et. al (2006), ranging between -5 (very uncomfortable) and +5 (very comfortable). The scales are presented in Appendix 4.
3.3.4.2. Participants’ preparation

Upon arrival, participants were given a description of the experimental session. They changed into their own shorts. Following careful instruction, each participant inserted a rectal thermometer (Grant Instruments, Cambridge, England) 10 cm beyond the rectal sphincter for measurement of core temperature ($T_c$) during the experiment. Participants then reported to the preparation room where they were weighed on a calibrated Mettler ID1 Multirange electronic scale (Mettler Toledo, Leicester, UK; resolution= 0.001kg). A water-bottle was weighed and provided to the participant who was allowed to drink ad-libitum from this stage. Participants were then fitted with a Polar heart rate monitor and watch (Polar Electro Oy, Kempele, Finland).

For measurement of $T_{sk}$, 4 wireless iButtons (Maxim Integrated Products, Inc., USA) were placed on the targeted (cooled) segment. For each segment, their positioning was chosen to cover an important part of the segment. In contrast, non-cooled segments only had one wireless iButton. All iButtons were on the right hand side of the body. Examples are shown on Figure 3.7.

Figure 3.7 Positioning of the wireless iButtons when the abdomen (left) or the forearm (right) is the cooled segment
Participants were then dressed in a one piece Lycra leotard (worn over briefs, iButtons and heart rate monitor). The custom-made high density Cool Tubesuit™ (Med-Eng Systems Inc., Canada) was then worn over the leotard, and its tightness was adjusted according to participants’ body size thanks to the snap fasteners.

Since each test consisted of the cooling of only one segment, it was not needed for the participants to wear the full WPS (i.e. top and trousers). Instead, participants wore a tracksuit trousers (cooled segment on the upper body) or a tracksuit top (cooled segment on the lower body). Finally, the compression/insulating Velcro-type support described in 3.2.1.1 was placed around the targeted segment.

3.3.4.3. Testing protocol

Phase 1 – Thermal neutrality

After preparation which lasted around 30 minutes in total, participants entered the climatic chamber set at 20°C and 40% RH. The cycle ergometer seat was first adjusted according to participants’ height, after which they sat down on a stool situated in front of the cooling system. At this stage, 28°C water was already circulating through the whole system to avoid running cold water through the WPS. The target body segment was plugged onto the switch board, and participants were asked to report their local thermal sensation after 2 minutes of perfusion. If thermal sensation was not neutral at that stage, the water bath temperature was set 1°C higher or lower, depending on the thermal sensation reported and participant reported their thermal sensation again 2 minutes after stabilisation of the water temperature. This procedure was repeated until a local thermal sensation of 0 (“neutral”) was reported. After reaching thermal neutrality, participants were asked to report overall thermal sensation and thermal comfort, as well as local thermal sensation and thermal comfort at each of these body segments: chest, abdomen, upper arms, lower arms, upper back, lower back, upper legs, and lower legs.
**Phase 2 – Cooling at rest**

Following the thermoneutrality determination the targeted segment was plugged onto the second water bath which was set at 20°C. Local and overall thermal sensations and comfort were asked after 5 and 10 minutes of cooling, after which the temperature of the water bath was reduced by 5°C. The water-bath temperature drop was sped up by briefly fully opening the heat exchanger valve, which let more water in from the industrial chiller and dropped the bath water temperature by 5°C in less than a minute. This 10 minute cooling cycle was done at water bath temperatures of 20, 15 and 10°C. Once the water-bath was set at 10°C, water was continuously pumped through the cooled segment at this temperature for the remainder of the experiment.

**Phase 3 – Exercise**

After the initial 30 minutes of cooling at rest, participants sat on the electromagnetically braked cycle ergometer (Lode Excalibur, Groningen, The Netherlands) and immediately started pedalling at 60 rpm, with a resistance equivalent to 30% of their predicted VO₂ max. The exercise lasted for 15 minutes, and participants continued to rate their local and overall thermal sensation and thermal comfort every 5 minutes. Water (10°C) was still continuously pumped through the suit to maintain a low Tsk for comparison between rest and exercise.

**Phase 4 – Post-exercise recovery**

After 15 minutes of exercise, participants sat down on the stool again, and rested for a post-exercise recovery period of 15 minutes. Similarly to the exercise period, participants still reported thermal sensation and thermal comfort every 5 minutes. Water (10°C) was still continuously pumped through the suit in order to maintain a low Tsk.
3.3.4.4. End of experiment

After 15 minutes of post-exercise recovery, participants were offered the possibility of re-warming their cooled body segment if they wished, after which the WPS was unplugged from the cooling system. Participants were then taken back to the preparation room where the compression support, tracksuit, WPS, leotard, heart rate monitor and iButtons were removed. After measuring body weight again and providing that their $T_c$ was below 38.5°C, participants were allowed to leave after removal of the rectal probe.

3.3.5. Data analysis

Data from each iButton and rectal thermistor was first synchronised with the specific timings of each corresponding test, in order to match temperature measurements to the corresponding thermal sensation and comfort values.

The following parameters at the end of each test phase were compared with repeated-measures Analysis of Variance (ANOVA): $T_{sk}$ (absolute and delta), $T_c$ (absolute and delta), local thermal sensation and comfort at the cooled segment, overall thermal sensation and comfort, and thermal sensitivity. To remain focussed on the present research aims, pairwise comparisons between body segments will not be presented for local thermal sensation or local thermal comfort; instead, pairwise comparisons will be provided for thermal sensitivity, which was calculated with 4 different definitions (and therefore equations) in mind:

1) The change in local thermal sensation per change in $T_{sk}$ at the targeted segment:
\[
\Delta \frac{LS}{\Delta T_{sk}}
\]

2) The change in overall thermal sensation per change in $T_{sk}$ at the targeted segment:
\[
\Delta \frac{OS}{\Delta T_{sk}}
\]
3) The change in *local thermal comfort* per change in $T_{sk}$ at the targeted segment:

$$\frac{\Delta LC}{\Delta T_{sk}}$$

4) The change in *overall thermal comfort* per change in $T_{sk}$ at the targeted segment:

$$\frac{\Delta OC}{\Delta T_{sk}}$$

In each case, $\Delta T_{sk}$ was calculated as the difference in $T_{sk}$ between the end of phase 1 (i.e. $T_{sk}$ at neutrality) and the end of each other phase (rest, exercise and recovery). For each definition, a 2-way repeated-measures ANOVA was performed to compare thermal sensitivity between the 8 body segments as well as between the 3 conditions, namely rest, exercise and recovery.

With 8 body segments being compared, multiple post-hoc comparisons are made with the risk of inflating type I error. This matter has been discussed in the literature (Bender and Lange, 1999; Perneger, 1998). Based on these discussions, it was decided that a Bonferroni may be overly conservative (pushing the limit P value for significance to 0.0063 for segments) for the present type of exploratory study, and would inflate type II error. It was therefore decided to provide the significant differences and trends ($0.05 \leq p \leq 0.1$) before correction for multiple comparisons and bring to the reader’s attention that these should be interpreted with multiple comparisons in mind (Havenith et al., 2008). In addition, significant differences after Bonferroni corrections for the multiple groups will also be reported, highlighting the strongest differences.

Statistical analysis was performed using IBM SPSS Statistics (version 19.0, Chicago, USA). The level of statistical significance was set at $p < 0.05$ for all statistical tests.
3.4. Results

3.4.1. Participants’ characteristics

Characteristics of the participants are presented in Table 3.1.

Table 3.1 Participants’ characteristics (n = 8)

<table>
<thead>
<tr>
<th></th>
<th>Height (cm)</th>
<th>Body weight (kg)</th>
<th>Age (y)</th>
<th>BF%</th>
<th>VO₂ max (ml ∙ kg⁻¹ ∙ min⁻¹)</th>
<th>Work load =30% VO₂ max intensity (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± SD</td>
<td>181.8 ± 2.5</td>
<td>78.3 ± 5.7</td>
<td>22.0 ± 3.5</td>
<td>10.1 ± 2.8</td>
<td>43.2 ± 3.0</td>
<td>79.1 ± 8.0</td>
</tr>
</tbody>
</table>

3.4.2. Skin temperature

Absolute values of $T_{sk}$ are presented in Figure 3.8. The values presented show $T_{sk}$ averaged over the 4 measurement sites on the cooled body segment (means of all participants).

Regarding changes in $T_{sk}$ ($\Delta T_{sk}$), the analysis revealed a significant main effect of body segment on $\Delta T_{sk}$ at the end of the resting period ($p < 0.0005$), at the end of the exercise period ($p = 0.001$) and at the end of the post-exercise recovery period ($p < 0.0005$). Despite these strong statistical significances, the differences between the segments were not large, highlighting a clear improvement in the efficacy of the WPS at cooling different segments to a similar degree (Figure 3.9).
Figure 3.8 Absolute values of $T_{sk}$ at each targeted body segment during the experiment ($n = 8$)

Figure 3.9 Decrease in $T_{sk}$ between the experiment commencement and the end of the cooling at rest, during exercise and post-exercise recovery.
Concerning $T_{sk}$ at the non-cooled body segments, these are presented in Appendix 5. With 7 iButtons at non-cooled segments per test, 8 tests per participants and 8 participants, the total number of individual iButton data files for non-cooled segments was 448. Since this was not the main focus of the present study and due to the lengthy analytical procedure required, values are presented only for one participant as an example. Additionally, mean skin temperature at non-cooled body segments (unweighed average) in each condition are presented below for one participant (Figure 3.10).

![Figure 3.10 Mean skin temperature at non-cooled body segments throughout the experiments (n = 1). Each line represents a different condition. For example, the pink line labelled “calf” shows the unweighed average $T_{sk}$ of the chest, abdomen, upper arm, lower arm, upper back, lower back and thigh whilst the calves are being cooled.]

3.4.3. Core temperature

In order to investigate whether skin cooling of different body segments results in different changes in $T_c$, it was initially decided to plot mean $T_c$ against time for each condition. However, despite testing participants at the same time of the day and
asking them not to exercise prior to any experiment, slight differences were found in the initial $T_c$ at the beginning of the experiment (Figure 3.11). These were low in magnitude (< 0.2°C) and non-significant; $F(7,49) = 1.38$, $p = 0.237$.

![Figure 3.11](image_url)  
Figure 3.11 Absolute values of $T_c$ throughout the experiment (absolute mean values; $n = 8$)

It was therefore decided to analyse $T_c$ as mean relative values and more specifically as the change in $T_c$ from the experiment commencement (Figure 3.12).

![Figure 3.12](image_url)  
Figure 3.12 Changes in $T_c$ throughout the test, compared between the segments cooled
The repeated measures ANOVA revealed no significant main effect of body segment; \( F(7, 49) = 1.81; \ p = 0.107 \), though the pairwise comparisons with Bonferroni adjustments showed statistically significant differences, mainly pointing to a lower \( T_c \) for the upper legs and a higher \( T_c \) for the lower back (Table 3.2).

### Table 3.2 \( \Delta T_c \): significant differences and trends (0.05 ≤ \( p \) ≤ 0.1) between body segments. *Trend before Bonferroni correction. † Significant difference before Bonferroni correction. # Significant difference after Bonferroni correction.

<table>
<thead>
<tr>
<th>Segment A</th>
<th>Segment B</th>
<th>Mean Difference A-B (°C)</th>
<th>( p )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Back</td>
<td>Upper legs</td>
<td>0.103</td>
<td>0.000 #</td>
</tr>
<tr>
<td>Lower Arms</td>
<td>Upper legs</td>
<td>0.073</td>
<td>0.012 †</td>
</tr>
<tr>
<td>Chest</td>
<td>Lower Back</td>
<td>-0.051</td>
<td>0.026 †</td>
</tr>
<tr>
<td>Upper Arms</td>
<td>Lower Back</td>
<td>-0.068</td>
<td>0.033 †</td>
</tr>
<tr>
<td>Upper legs</td>
<td>Lower legs</td>
<td>-0.045</td>
<td>0.059 *</td>
</tr>
<tr>
<td>Lower Back</td>
<td>Lower legs</td>
<td>0.058</td>
<td>0.062 *</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Upper legs</td>
<td>0.059</td>
<td>0.078 *</td>
</tr>
</tbody>
</table>

Furthermore, a significant main effect of time was found, \( F(12, 84) = 9.47; \ p < 0.0005 \). Despite this strong significance, the changes in \( T_c \) with time were very low in magnitude, with a drop of 0.1 to 0.2°C between neutrality and the end of the cooling period, and an increase of a similar magnitude during the exercise part of the protocol (Figure 3.12). Finally, no significant segment*time interaction effect was found: \( F(84, 588) = 1.09; \ p = 0.279 \).

### 3.4.4. Thermal sensation

#### 3.4.4.1. Local thermal sensation

The statistical analysis revealed a main effect of segment on local thermal sensation: \( F(7, 49) = 22.91; \ p < 0.0005 \) as well as a main effect of time: \( F(2, 14) = 188.74; \ p < 0.0005 \). Comparing local thermal sensations between the start and the end of each phase, pairwise comparisons of the main time effect revealed a significant drop in local thermal sensation at the end of the cooling period (\( p < 0.0005 \)), a significant
increase during the exercise phase ($p < 0.0005$) and a significant drop again at the end of the post-exercise recovery period ($p < 0.0005$). Local thermal sensation was also significantly colder at the end of the rest period than at the end of the post-exercise recovery period ($p < 0.0005$). A segment*time interaction effect was also found: $F(15, 98) = 3.29; p < 0.0005$. Absolute values of local thermal sensations at the cooled segment are presented in Figure 3.13.

![Figure 3.13](image)

**Figure 3.13** Evolution of local thermal sensation at each cooled body segment during the experiment ($n = 8$)

### 3.4.4.2. Overall thermal sensation

The statistical analysis revealed a significant main effect of segment on overall thermal sensation: $F(7,49) = 11.68; p < 0.0005$ as well as a main effect of time: $F(2, 14) = 65.36; p < 0.0005$. Similarly to local thermal sensation, pairwise comparisons of the main time effect revealed a significant drop in overall thermal sensation at the end of the cooling period ($p < 0.0005$), a significant increase during the exercise phase ($p < 0.0005$) and a significant drop again at the end of the post-exercise recovery period ($p = 0.001$). Overall thermal sensation was also significantly colder at the end of the rest period than at the end of the post-exercise recovery period ($p$...
No significant segment*time interaction effect was however found, F(14, 98) = 1.01, p = 0.45. Absolute values of overall thermal sensations during the cooling of each body segment are presented in Figure 3.14.

![Figure 3.14 Evolution of overall thermal sensation at each cooled body segment during the experiment (n = 8)](image)

### 3.4.5. Thermal comfort

#### 3.4.5.1. Local thermal comfort

The statistical analysis revealed a significant main effect of segment on local thermal comfort: F(7, 49) = 4.91; p < 0.0005 as well as a main effect of time: F(2, 14) = 56.28; p < 0.0005. Pairwise comparisons of the main time effect revealed a significant drop in local thermal comfort at the end of the cooling period (p < 0.0005), a significant increase during the exercise phase (p < 0.0005) and a significant drop again at the end of the post-exercise recovery period (p = 0.001). Local thermal comfort was also significantly less comfortable at the end of the rest period than at the end of the post-exercise recovery period (p < 0.0005).
No significant segment*time interaction effect was however found, $F(14, 98) = 1.01$, $p = 0.93$. Absolute values of local thermal comfort during the cooling of each body segment are presented in Figure 3.15.

![Figure 3.15](image)

**Figure 3.15** Evolution of local thermal comfort at each cooled body segment during the experiment ($n = 8$)

### 3.4.5.2. Overall thermal comfort

Mauchly's sphericity test revealed a violation of sphericity. After Greenhouse-Geisser correction, the ANOVA revealed a significant main effect of segment on overall thermal comfort: $F(3,22) = 3.67$; $p = 0.026$ as well as a main effect of time: $F(1,8) = 11.69$; $p = 0.009$. Pairwise comparisons of the main Time effect revealed a significant drop in overall thermal comfort at the end of the cooling period ($p < 0.0005$), a significant increase during the exercise phase ($p = 0.012$) but no significant difference between the end of the exercise and the end of the post-exercise recovery ($p = 1.00$). Overall thermal comfort was also significantly less...
comfortable at the end of the rest period than at the end of the post-exercise recovery period ($p < 0.0005$).

A significant segment*time interaction effect was also found, $F(4, 28) = 4.59$, $p = 0.006$. Absolute values of overall thermal comforts during the cooling of each body segment are presented in Figure 3.16.

![Figure 3.16](image)

**Figure 3.16** Evolution of overall thermal comfort at each cooled body segment during the experiment ($n = 8$)

### 3.4.6. Thermal sensitivity

In the present study, thermal sensitivity is analysed assuming that skin temperature is the *driver* for thermal sensation and thermal comfort. Four definitions of thermal sensitivity are therefore analysed in this section, namely the effect of a change in local skin temperature on local thermal sensation ($\Delta S/\Delta T_{sk}$), overall thermal sensation ($\Delta OS/\Delta T_{sk}$), local thermal comfort ($\Delta LC/\Delta T_{sk}$), and on overall thermal comfort ($\Delta OC/\Delta T_{sk}$).
3.4.6.1. Change in local thermal sensation per change in local $T_{sk}$ ($\Delta LS/\Delta T_{sk}$)

Figure 3.17 depicts $\Delta LS/\Delta T_{sk}$ for each body segment cooling and in each condition.

Mauchly's sphericity test revealed a violation of sphericity for body segments and for conditions. After Greenhouse-Geisser correction, the statistical analysis revealed a significant main effect of body segment: $F(2, 16) = 6.36; p = 0.008$. Pairwise comparison with Bonferroni corrections revealed several significant differences and tendencies towards significance ($0.05 \leq p \leq 0.1$). These are listed in Table 3.3.
A significant main effect of condition was also found; \( F(1, 8) = 230.15; p < 0.0005 \). The pairwise comparison suggested a significantly greater \( \Delta LS/\Delta T_{sk} \) at rest than during exercise \( (p < 0.0005) \) and recovery \( (p < 0.0005) \), and a significantly greater \( \Delta LS/\Delta T_{sk} \) during recovery than exercise \( (p < 0.0005) \). Finally, a significant body segment * condition interaction effect was also found; \( F(14, 98) = 3.8; p < 0.0005 \).

### 3.4.6.2. Change in overall thermal sensation per change in local \( T_{sk} \) (\( \Delta OS/\Delta T_{sk} \))

Figure 3.18 depicts \( \Delta OS/\Delta T_{sk} \) for each body segment cooling and in each condition.
Mauchly’s sphericity test revealed a violation of sphericity for conditions but not for body segment. The statistical analysis revealed a significant main effect of body segment: $F(7, 49) = 5.90; p < 0.0005$. Pairwise comparison revealed several significant differences and tendencies towards significance ($0.05 < p < 0.1$). These are listed in Table 3.4.

### Table 3.4 \( \Delta OS/\Delta T_{sk} \) : significant differences and trends ($0.05 \leq p \leq 0.1$) between body segments. *Trend before Bonferroni correction. † Significant difference before Bonferroni correction. # Significant difference after Bonferroni correction.

<table>
<thead>
<tr>
<th>Segment A</th>
<th>Segment B</th>
<th>Mean Difference (A-B)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Arms</td>
<td>Lower legs</td>
<td>0.353</td>
<td>&lt; 0.0005 #</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Upper Arms</td>
<td>-0.332</td>
<td>0.001#</td>
</tr>
<tr>
<td>Upper Back</td>
<td>Lower legs</td>
<td>0.204</td>
<td>0.005 #</td>
</tr>
<tr>
<td>Upper legs</td>
<td>Lower legs</td>
<td>0.269</td>
<td>0.005 #</td>
</tr>
<tr>
<td>Chest</td>
<td>Upper Arms</td>
<td>-0.229</td>
<td>0.007 †</td>
</tr>
<tr>
<td>Upper Arms</td>
<td>Lower Arms</td>
<td>0.287</td>
<td>0.008 †</td>
</tr>
<tr>
<td>Lower Arms</td>
<td>Upper Back</td>
<td>-0.139</td>
<td>0.011 †</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Lower Back</td>
<td>-0.233</td>
<td>0.012 †</td>
</tr>
<tr>
<td>Lower Back</td>
<td>Lower legs</td>
<td>0.254</td>
<td>0.013 †</td>
</tr>
<tr>
<td>Chest</td>
<td>Lower legs</td>
<td>0.123</td>
<td>0.024 †</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Upper Back</td>
<td>-0.183</td>
<td>0.026 †</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Upper legs</td>
<td>-0.248</td>
<td>0.034 †</td>
</tr>
<tr>
<td>Lower Arms</td>
<td>Lower Back</td>
<td>-0.189</td>
<td>0.074 *</td>
</tr>
<tr>
<td>Upper Arms</td>
<td>Upper Back</td>
<td>0.148</td>
<td>0.078 *</td>
</tr>
<tr>
<td>Chest</td>
<td>Abdomen</td>
<td>0.102</td>
<td>0.099 *</td>
</tr>
</tbody>
</table>
After correction of degrees of freedom using Greenhouse-Geisser, a significant main effect of condition was found: $F(1, 7) = 77.55; p < 0.0005$. The pairwise comparison revealed the same general pattern as for $\Delta LS/\Delta T_{sk}$, namely a significantly greater $\Delta OS/\Delta T_{sk}$ at rest than during exercise ($p < 0.0005$) and recovery ($p < 0.0005$), and a significantly greater $\Delta OS/\Delta T_{sk}$ during recovery than exercise ($p < 0.0005$). Finally, no significant body segment * condition interaction effect was found; $F(14, 98) = 1.36; p = 0.188$.

3.4.6.3. Change in local thermal comfort per change in local $T_{sk}$ ($\Delta LC/\Delta T_{sk}$)

Figure 3.19 depicts $\Delta LC/\Delta T_{sk}$ for each body segment cooling and in each condition.

![Figure 3.19 Thermal sensitivity mathematically defined as $\Delta LC/\Delta T_{sk}$](image)

Mauchly's sphericity test revealed a violation of sphericity for body segments and for conditions. After Greenhouse-Geisser correction, the statistical analysis revealed a strong tendency towards significance for body segment: $F(3, 19) = 3.02; p = 0.060$. Pairwise comparisons revealed several significant differences and tendencies towards significance (Table 3.5).
Table 3.5 $\Delta LC/\Delta T_{sk}$: significant differences and trends ($0.05 \leq p \leq 0.1$) between body segments. *Trend before Bonferroni correction. ¥ Significant difference before Bonferroni correction. ¥ Significant difference after Bonferroni correction.

<table>
<thead>
<tr>
<th>Segment A</th>
<th>Segment B</th>
<th>Mean Difference (A-B)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper legs</td>
<td>Lower legs</td>
<td>0.206</td>
<td>0.003 ¥</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Upper Arms</td>
<td>-0.207</td>
<td>0.010 ¥</td>
</tr>
<tr>
<td>Chest</td>
<td>Abdomen</td>
<td>0.161</td>
<td>0.013 ¥</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Upper Back</td>
<td>-0.124</td>
<td>0.014 ¥</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Lower Arms</td>
<td>-0.186</td>
<td>0.015 ¥</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Lower Back</td>
<td>-0.259</td>
<td>0.017 ¥</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Upper legs</td>
<td>-0.263</td>
<td>0.019 ¥</td>
</tr>
<tr>
<td>Upper Arms</td>
<td>Lower legs</td>
<td>0.149</td>
<td>0.071 *</td>
</tr>
<tr>
<td>Upper Back</td>
<td>Upper legs</td>
<td>-0.140</td>
<td>0.080 *</td>
</tr>
<tr>
<td>Chest</td>
<td>Upper Back</td>
<td>0.038</td>
<td>0.086 *</td>
</tr>
</tbody>
</table>

After Greenhouse-Geisser correction, a significant main effect of condition was found: $F(1, 7) = 63.53; p < 0.0005$. The pairwise comparisons showed the same general pattern as that found for $\Delta LS/\Delta T_{sk}$ and $\Delta OS/\Delta T_{sk}$, namely a significantly greater $\Delta LC/\Delta T_{sk}$ at rest than during exercise ($p < 0.0005$) and recovery ($p < 0.0005$), and a significantly greater $\Delta LC/\Delta T_{sk}$ during recovery than exercise ($p = 0.001$). Finally, no significant body segment * condition interaction effect was found; $F(14, 98) = 1.42$ $p = 0.160$.

### 3.4.6.4. Change in overall thermal comfort per change in local $T_{sk}$ ($\Delta OC/\Delta T_{sk}$)

Figure 3.20 depicts $\Delta OC/\Delta T_{sk}$ for each body segment cooling and in each condition.
Mauchly’s sphericity test revealed a violation of sphericity for conditions but not for body segments. The statistical analysis revealed a significant main effect of body segment: $F(7, 49) = 2.34; \ p = 0.038$. Pairwise comparisons revealed several significant differences and tendencies towards significance (Table 3.6).

Table 3.6 $\Delta OC/\Delta T_{sk}$: significant differences and trends ($0.05 \leq p \leq 0.1$) between body segments. *Trend before Bonferroni correction. * Significant difference before Bonferroni correction. # Significant difference after Bonferroni correction.

<table>
<thead>
<tr>
<th>Segment A</th>
<th>Segment B</th>
<th>Mean Difference (A-B)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest</td>
<td>Abdomen</td>
<td>0.112</td>
<td>0.005 #</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Lower Back</td>
<td>-0.252</td>
<td>0.006 #</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Upper Arms</td>
<td>-0.126</td>
<td>0.011 ϱ</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Upper legs</td>
<td>-0.199</td>
<td>0.023 ϱ</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Upper Back</td>
<td>-0.105</td>
<td>0.028 ϱ</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Lower Arms</td>
<td>-0.094</td>
<td>0.030 ϱ</td>
</tr>
<tr>
<td>Lower Arms</td>
<td>Lower Back</td>
<td>-0.158</td>
<td>0.062 *</td>
</tr>
<tr>
<td>Upper Back</td>
<td>Lower Back</td>
<td>-0.146</td>
<td>0.095 *</td>
</tr>
<tr>
<td>Upper Arms</td>
<td>Lower Back</td>
<td>-0.126</td>
<td>0.096 *</td>
</tr>
</tbody>
</table>

After Greenhouse-Geisser correction, a significant main effect of condition was found: $F(1, 8) = 18.42; \ p = 0.003$. The pairwise comparisons showed the same general pattern between rest and exercise as that found for the other variables presented earlier, namely a significantly greater $\Delta OC/\Delta T_{sk}$ at rest than during
exercise (p = 0.001) and recovery (p < 0.0005). However, no significant difference was found in $\Delta OC/\Delta T_{sk}$ between exercise and recovery (p = 0.581). Finally, a significant body segment * condition interaction effect was also found; $F(14, 98) = 4.80 \ p < 0.0005$.

### 3.4. Discussion

In the present study, a second attempt was made to answer two fundamental questions in applied thermophysiology. The first question relates to the distribution of thermal sensitivity to cold across the body, and the second one aims to explore the influence of exercise on thermal sensitivity to cold. In order to investigate these, the equipment and the experimental protocol have been improved according to the limitations highlighted in the previous chapter. The present discussion will first clarify whether these limitations still apply in the present context, and will then examine the data in relation to the two research questions.

#### 3.4.1. Improvements of the equipment and protocol

One concern highlighted in study 1 was regarding core temperature, and more specifically its different level at the onset of each segment’s cooling. To counteract this potential issue, it was decided to test only one segment only during each experiment. As a result, $T_c$ was nearly exactly the same at the cooling onset of each body segment.

Similarly to the issue of $T_c$, results of study 1 also highlighted that each body segment should be at its temperature of thermal neutrality before cooling it down, and this was achieved in the present protocol by allowing participant to change the water temperature ad libitum until thermal sensation reached a neutral state, before the cooling start.
Finally, regarding the total change in \( T_{sk} \) between the onset and the cessation of cooling, large variations were highlighted between body segments in the previous study, which created complications in the data interpretation. Parameters which determine \( T_{sk} \) include internal heat, blood flow, body fat and external loss. After improving the tightness of the WPS, insulating the cooled segments, and measuring \( T_{sk} \) at several locations within each cooled segment, large improvements were made in the consistency found in \( \Delta T_{sk} \) between body segments. The existence of a significant effect of body segment on \( \Delta T_{sk} \) may give the impression that this was not successfully overcome; However, the differences were of low magnitude, and all body segments were cooled by at least 5°C (Figure 3.9).

It can therefore be concluded that the limitations discovered in chapter 2 were dealt with and solved adequately in the present study, which should allow to provide answers to the research questions initially posed.

### 3.4.2. Regional differences in thermal sensitivity to cold

#### 3.4.2.1. Surface area

Different definitions exist for thermal sensitivity. Specifically, some authors have used measures relative to a surface area either by calculation (e.g.: Burke and Mekjavic, 1991) or by using one unique stimulus surface area (e.g.: Cotter, 1997; Nakamura et al., 2008; Ouzzahra et al., 2012). In contrast, other authors did not take into account the total surface of each stimulated area. For example, Tipton and Golden (1987) ignored the 5% difference in exposed surface area body segments compared during water immersion. However, theoretically the surface area of the cooled region will influence the thermosensitive response (Zotterman, 1953). This was confirmed by Stevens (1979) who demonstrated that colder thermal sensations are reported when a 20 cm\(^2\) stimulus is applied compared with 9 cm\(^2\), even if both stimuli are at the same temperature.
In the present study, it was decided to compare body segments without correcting them for surface area. The rationale for this type of analysis lies in the applicability of the data. For example, finding out that the skin is not very sensitive to cold per surface area at the upper leg compared to the abdomen could lead to think that the abdomen needs to be protected from the cold more than the thighs. However, we have two thighs and together they represent a much larger surface area than the abdomen. Therefore, according to the principle of spatial summation of afferents activity (Stevens, 1979), both upper legs being cooled down simultaneously may in reality result in a more intense thermal sensation than when the abdomen is cooled. To avoid such misinterpretation of the data, it was decided not to correct the present thermal sensitivity values according to the relative surfaces stimulated. Instead, values of thermal sensitivity were presented and compared as whole body segments, so that the data is directly applicable in the clothing and thermal manikin context. Surface area will however be taken into account in the interpretation of the data and its comparison with previous results.

3.4.2.2. Core temperature

As expected, $T_c$ decreased during the resting phase of the experiment, and increased during the exercise condition. Despite being significant, the changes were of low magnitude in all cases. The greatest drop in $T_c$ was found in response to upper legs cooling, and this was significantly greater than when cooling the lower back or the lower arms. The first reason behind this may be related to the cooled surface area. Indeed, the upper legs were the largest cooled segment in the present study, and it seems therefore logical that their cooling results in the greatest drop in $T_c$. Furthermore, this greater drop in $T_c$ when cooling the thighs was especially more pronounced from the initial phase of exercise, and may therefore be related to the redistribution of blood flow from major organs to the working muscles during exercise (e.g.: Qamar and Read, 1987). Indeed, upper legs cooling at rest is likely to have cooled down not only the skin but also deeper tissues such as the quadriceps muscles, which means that the blood perfusing these
muscles during exercise must have been kept cooler than when a different segment was cooled. This would result in $T_c$ being maintained lower for longer. Moreover, cooling this body segment during exercise would have inevitably delayed and lessened the increase in $T_c$ as the cold water running through the suit would effectively absorb some of the metabolic heat produced. This proposition is also confirmed by the fact that $T_c$ was amongst the lowest when the lower legs were cooled down (Figure 3.11) despite their lower area. Finally, it must be noted that core temperature responses vary according to measurement site. As described in chapter 1, $T_c$ is essentially the blood temperature in the circulation, and the gold standard for $T_c$ measurement is the temperature of the blood from the pulmonary artery (Farnell et al., 2005). It is important to recognise therefore that the differences found in $T_c$ depending on the segment cooled may have differed according to the $T_c$ measurement site, and it would be relevant to investigate this factor in future research.

3.4.2.3. Thermal sensation

Looking at the results in terms of change in local thermal sensation per change in $T_{sk}$, the present study confirms that thermal sensitivity to cold varies between body segments. More specifically, the $\Delta LS/\Delta T_{sk}$ thermal sensitivity sequence at rest, from relatively sensitive to insensitive, was the following: lower back, upper legs and upper arms, lower arms, chest, upper back, lower legs, and abdomen. The differences were high in magnitude between the two extremes, as $\Delta LS/\Delta T_{sk}$ was almost twice as high at the lower back compared with the abdomen. Such differences are attributable to several factors. The total number of thermoreceptors stimulated, which is the product of the thermoreceptor density and surface area stimulated, is arguably the most important factor contributing to thermal sensitivity. Although it is difficult to quantitatively evaluate differences in the density of skin thermoreceptors in humans, the density of cold spots would be expected to correlate positively with the density of cold receptors (Hensel, 1981). Previous research has highlighted differences in cold spots density across the body.
For example, Strughold and Porz (1931) found that the averaged cold spot densities in spots per cm$^2$ for each segment were as follows: abdomen (10.3), chest (9.6), lower back (7.8), forearm (6.8), upper arm (5.8), calf (5.0), and thigh (4.9). Multiplying these values by the total surface area stimulated for each segment in the present study should provide the number of cold spots theoretically stimulated. However when ranked from lowest to highest, the order of these values does not match very well with the thermal sensitivity sequence found in the present study, as listed in Table 3.7.

<table>
<thead>
<tr>
<th>Body segment</th>
<th>Cold spot / cm$^2$ (Strughold and Porz, 1931)</th>
<th>Surface stimulated in the present study (cm$^2$)</th>
<th>Cold spots theoretically stimulated in the present study (lowest to highest)</th>
<th>Thermal sensitivity ($\Delta S / \Delta T_{th}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Arms</td>
<td>6.8</td>
<td>1000</td>
<td>6800</td>
<td>1.52</td>
</tr>
<tr>
<td>Lower Back</td>
<td>7.8</td>
<td>1100</td>
<td>8580</td>
<td>1.69</td>
</tr>
<tr>
<td>Lower Legs</td>
<td>5.8</td>
<td>1800</td>
<td>9000</td>
<td>1.12</td>
</tr>
<tr>
<td>Upper Arms</td>
<td>5.8</td>
<td>1600</td>
<td>9280</td>
<td>1.56</td>
</tr>
<tr>
<td>Abdomen</td>
<td>10.3</td>
<td>1100</td>
<td>11330</td>
<td>0.88</td>
</tr>
<tr>
<td>Chest</td>
<td>9.6</td>
<td>1200</td>
<td>11520</td>
<td>1.43</td>
</tr>
<tr>
<td>Upper Legs</td>
<td>4.9</td>
<td>3400</td>
<td>16660</td>
<td>1.56</td>
</tr>
</tbody>
</table>

Two reasons may explain these discrepancies. First, it has been previously suggested that the existence of a weighing of thermoafferent information by the integration centre in the CNS may partially explain the regional differences in thermal sensitivity to cold (Burke and Mekjavić, 1991). The second reason is related to the exact location of sensory spots measurements sites. Indeed, thermal sensitivity to cold may not only vary between body segments, but also within each segment. The density of thermoreceptors may therefore also vary within body segments, which means that the actual number of cold spots for each segment may be very different from those listed in Table 3.7. This also suggests that Strughold and Porz’ cold spots measurements may either be an under- or overestimation of the average cold spots density across the whole segment. In the present study, whole body segments were cooled and therefore involved in the thermal sensation rated by participants. This question of uniformity of thermal sensitivity within body
segments will be raised further in this thesis. It is therefore possible that.
Realistically, it is likely that a complex interaction of the two factors presented
above explain the ranking of thermal sensitivity to cold found in the present study.

Regarding the effects of local cooling on overall thermal sensation at rest, several
significant differences were also found between body segments. The ranking of
$\Delta OS/\Delta T_{sk}$ was somewhat different from that of $\Delta LS/\Delta T_{sk}$ with the sequence from
high to low thermal sensitivity being as followed: upper arms, upper legs, upper
back, lower back, chest, lower arms, lower legs and abdomen. Compared with
$\Delta LS/\Delta T_{sk}$, the most pronounced difference in terms of sensitivity sequence was
found at the upper back, which despite being towards the least sensitive body
segments in terms of $\Delta LS/\Delta T_{sk}$, was also towards the most thermally sensitive
segments in terms of $\Delta OS/\Delta T_{sk}$. One explanation for this difference is related to the
importance of other segments in the rating of overall sensation. The upper back
and lower back are adjacent body segments, and as shown in Appendix 5, cooling
the upper back also had a cooling effect on the lower back ($\approx 1.5^\circ C$ drop). Since the
lower back was found to be an area of high thermal sensitivity, even a slight
decrease in $T_{sk}$ at this area would intensify the overall cold sensation. Likewise,
cooling the upper arms caused a reduction of $\approx 1^\circ C$ at the lower back, thighs and
calves, which would undoubtedly contribute to the overall thermal sensation and
may therefore explain the high $\Delta OS/\Delta T_{sk}$ found at the upper arms.

The thermal sensitivity sequence in terms of $\Delta OS/\Delta T_{sk}$ is expected to be the result of
a complex interaction between the thermal transfer dynamics and the local thermal
sensitivities of each body segments. In their study, Burke and Mekjavić (1991)
explain that the assessment of regional cutaneous cold sensitivity requires that
unexposed skin regions remain thermoneutral during local cooling. For that
purpose, they used a special immersion suit which seals each body segment with
rubber covers, thereby protecting regions adjacent to the stimulated one from
being exposed to water. In contrast, Tipton and Golden (1987) found a cooling of
unexposed skin regions by 4 to 5$^\circ C$, which according to Burke and Mekjavić (1991)
may have obscured a higher cold sensitivity. In the present study, keeping
unexposed regions at a level of thermal neutrality could have been achieved by perfusing them with water set at a thermoneutral temperature. However, this was not incorporated in the protocol because it would not replicate the natural thermal transfers which would normally occur in a situation where one individual body segment is cooled without any means of keeping the other segments at thermal neutrality. Considering that the present research will be applied in a clothing context, it was decided that allowing natural thermal transfers would provide a more applicable measurement of local and overall thermal sensitivity to cold.

3.4.2.4. Thermal comfort

Significant differences in thermal sensitivity were found between body segments in terms of local thermal comfort per change in skin temperature \((\Delta LC/\Delta T_{sk})\). The sequence from most sensitive to least sensitive at rest was as follows: lower back, lower arms, upper legs, upper arms, chest, upper back, lower legs and abdomen. This sequence is the same as for \(\Delta LS/\Delta T_{sk}\) with the exception of the lower arms, which when cooled down have a relatively greater impact on local thermal comfort than on local thermal sensation compared to the other body segments. It should however be noted that no significant differences existed between the lower back, upper legs and upper arms and lower arms, which suggests that these differences in ranking order may be of little importance in a practical application context.

Thermal comfort is an important factor in human thermoregulation, because it drives an individual to search for the appropriate thermal environment or to make postural changes to maintain a thermoneutral and thermally comfortable state. Thermal comfort depends on skin temperature when the internal body temperature is constant (Marks & Gonzalez, 1974), but is also affected by the internal thermal state when not constant (Chatonnet & Cabanac, 1965; Mower, 1976). Nakamura and colleagues (2008) found that individually cooling the chest, abdomen and thigh for 90 seconds resulted in a similar level of local thermal discomfort, whereas cooling the face did not induce any change in local thermal comfort values. Their stimulator was of a unique surface area for all body sites, while in the present study
the stimulus was of a greater surface at the thighs. The finding that the thighs induced a significantly higher level of \( \Delta LC/\Delta T_{sk} \) than the abdomen is therefore consistent with Nakamura’s results, and may mainly reflect the surface area of stimulation. The present results however suggest that a given decrease in \( T_{sk} \) will have a significantly greater influence on local thermal comfort at the chest than the abdomen which both have very similar surface areas. Furthermore, no significant differences were found between the chest and the thighs. The explanation for these differences may be related to the exact location of the stimulator in Nakamura’s study. Indeed, as explained in 3.4.2.3, regional differences in sensitivity to cold may exist within body segments and the positioning of Nakamura’s thermal stimulators at the chest and thigh would therefore affect inter-segmental differences. It must also be noted that Nakamura’s protocol consisted of cooling the regions in a mildly cold (21.3°C) or mildly hot (32.5°C) environment whilst wearing only shorts. This means that participants did not start from thermal neutrality before the beginning of cooling, which is likely to affect participants’ response to local cooling. Moreover, the short duration and low level of \( \Delta T_{sk} \) \( \approx 2°C \) also means that a direct comparison between Nakamura’s results and the present data is not entirely suitable. To the best of our knowledge, the present study is the first to provide regional differences in local thermal comfort resulting from whole body segments cooling starting from a neutral state.

Regarding the effects of regional cooling on overall thermal comfort, the present results showed the following \( \Delta OC/\Delta T_{sk} \) thermal sensitivity sequence at rest (from relatively sensitive to insensitive): lower back, upper legs, upper arms, chest, upper back, lower legs, lower arms, and abdomen. This sequence is very similar to the \( \Delta LC/\Delta T_{sk} \) with the exception of the lower arms, suggesting that the lower arms have a relatively low impact on overall thermal comfort despite evoking a relatively high level of local discomfort. The sequence also slightly differed between \( \Delta OS/\Delta T_{sk} \) and \( \Delta OC/\Delta T_{sk} \), which is in agreement with Nakamura and colleagues (2008) who found that regional differences in temperature sensation were not seen with stimulation that did produce regional differences in thermal comfort. This observation makes it unlikely that regional differences in thermal comfort can be entirely explained by
the properties and distribution of peripheral thermoreceptors. A more plausible explanation is that CNS processing is responsible for the production of regional differences in thermal comfort (Nakamura et al., 2008). During the process of overall thermal comfort rating, it is likely that each body area affects the reported value in relation to temperature-related inputs and to the corresponding weighing factors defining the influence of each local area on overall thermal comfort. Previous studies have shown that feelings of warmth and cold correlate with neural activity in the insular cortex (Craig et al., 2000; Olausson et al., 2005). Similarly, the amygdala, mid-orbitofrontal and pregenual cingulate cortex, as well as the ventral striatum have been implicated in the genesis of thermal comfort (Kanosue et al., 2002; Rolls et al., 2008).

The overall thermal comfort regional differences found in the present study may be explained by several factors. One main justification is the surface area stimulated, in the same way as this would influence overall sensation. This is unlikely to be the only reason however, as significant differences were found between the chest and the abdomen, as well as between the lower back and the abdomen which were all stimulated with an almost equal surface area. The low importance of a reduction in abdomen $T_{sk}$ on overall thermal comfort may be related to the role of thermal discomfort, and to the potential impact which body fat may have on it. Indeed, the basic function of temperature sensation and thermal discomfort is to drive an individual to search for the appropriate thermal environment, in order to avoid changes in internal temperature. Moreover, it is well reported that the central abdominal region is the highest in adipose tissue in men (e.g.: Arner, 1997). It seems therefore coherent that low temperatures in the abdominal regions have a low impact on overall thermal comfort, because it constitutes a low “risk” of internal cooling thanks to the insulating role of subcutaneous fat. Similarly, body areas remote from the body core are also expected to have a lower impact on thermal comfort compared to more central body segments. This may partially explain the greater $\Delta OC/\Delta T_{sk}$ found at the upper arms compared with lower arms, and at the upper legs compared with lower legs, although these differences did not reach statistical significance.
Realistically, the regional differences in thermal sensitivity found in the present study reflect a complex interaction of several factors occurring when a cold stimulus is applied at a specific body segment. It is highly interesting and relevant that a body segment causing a high level of cold local sensation will not necessarily result in an intense overall cold sensation. Similarly, an intense feeling of cold does not automatically translate into a great level of local or overall thermal discomfort. This partial independence of local and overall thermal sensation and thermal comfort reflects the existence of complex mechanism of integration at the CNS, which presumably takes into account the surface area stimulated, the density of thermoreceptors present at that body segment, and the risk that skin cooling at that region will result in a core temperature decrease.

It is important to note that the regional differences found in the present study must be applied hand in hand with $T_{sk}$ data. It would indeed only be appropriate to provide extra protection against the cold in a thermally sensitive area if this area is subject to important drops in $T_{sk}$.

### 3.4.3. The effects of exercise on thermal sensitivity

To the best of our knowledge, the present study is the first to offer comparisons between rest and exercise for thermal sensation and thermal comfort during continuous cooling of whole body segments. To achieve such a comparison, it was decided to fundamentally change the protocol used in study 1. Instead of starting the cooling period from an already exercising state, the current protocol consisted of starting the exercise from an already cooled state. This also allows a better analysis of the transition between rest and exercise, and from exercise to recovery.

In the present study, thermal sensitivity was analysed as a change in subjective perceptions per change in $T_{sk}$ at the cooled segment. Another option would have been to analyse absolute values of thermal sensation and thermal comfort, based on the fact that each segment is cooled with the same water temperature and for the same duration. However, as shown in study 1, the total change in skin
temperature may vary between body segments due to several technical and physiological factors, and these variations will affect comparisons between body segments. Although the variations between segments were small in the present study due to the equipment improvements, slight differences remained between body segments (Figure 3.9). Therefore, not using the relative values in the analysis in thermal sensitivity may result in an overestimation of thermal sensitivity for segments where $T_{sk}$ dropped slightly more, or vice-versa.

Four definitions of thermal sensitivity are therefore analysed in this section, namely the effect of a change in local skin temperature on local thermal sensation ($\Delta LS/\Delta T_{sk}$), overall thermal sensation ($\Delta OS/\Delta T_{sk}$), local thermal comfort ($\Delta LC/\Delta T_{sk}$), and on overall thermal comfort ($\Delta OC/\Delta T_{sk}$). In this section, the effects of exercise on thermal sensitivity in terms of thermal sensation and thermal comfort will be discussed separately.

### 3.4.3.1. Thermal sensation

The present results showed that participants perceived a less intensely cold local thermal sensation at the cooled segment when exercising, despite a decrease in $T_{sk}$ by several °C compared with resting values. This effect translated into a significant decrease in $\Delta LS/\Delta T_{sk}$ during exercise compared with rest. Such a decrease in thermal sensitivity to cold during exercise has not been demonstrated previously.

The first parameter which comes in mind to explain the effect of exercise on thermal sensitivity is $T_c$. Indeed, if thermal sensation results from the complex integration of several parameters in the CNS in order to assess the risk of a drop in $T_c$, it would then seem logical that an increase in $T_c$ would render a cold external stimulus less “alarming”, and may therefore be perceived less intensely. However, previous research has suggested that the intensity of thermal sensations resulting from a given thermal stimulus was not affected by passive (exogenous) thermal exposures. Specifically, Mower (1976) found that fluctuations in $T_c$ achieved passively in a bath have an effect on the pleasantness of a thermal stimulus, but not
on its intensity. Moreover, despite being significant, the increases in $T_c$ during exercise found in the present study were of very low magnitude (< 0.2°C in most cases), which makes it unlikely to be the only parameter explaining such changes in thermal sensation. This suggests that the decrease in local cold sensation intensity found in the present study may also be the result of another physiological change occurring during exercise.

One potentially important parameter is muscle temperature. Gagge and colleagues (1969) suggested that during transients caused at the start of exercise in a hot environment (30°C), the rapid rise in muscle temperature may contribute to the sudden rise in temperature sensation and thermal discomfort. In the present study, $\Delta LS/\Delta T_{sk}$ during exercise was lowest at the lower legs and upper legs, which corresponds well with the main muscles used during cycle ergometry. This is thus in agreement with the hypothesis that muscle temperature may play a role in thermal sensitivity, as the leg muscles must have increased in temperature during the exercise bout. In fact, the $\Delta LS/\Delta T_{sk}$ value found at the lower legs at the end of 15min cycling was negative, suggesting that a decrease in $T_{sk}$ at the lower legs effectively results in an increase in local thermal sensation (i.e. warmer sensation than at the start) at that stage. This should of course not be interpreted as an increase in thermal sensation resulting from a decrease in $T_{sk}$. Rather, this may reflect that internal temperature, both in terms of $T_c$ and muscles temperature play a role in local thermal sensation ratings. This would however need to be experimentally verified in future research including muscle temperature measurements. Other possible causes will be discussed later.

Looking at overall thermal sensation data, it seems important to mention that thermal sensitivity defined as $\Delta OS/\Delta T_{sk}$ during exercise must be interpreted with care. As shown in Figure 3.10, mean $T_{sk}$ at non-cooled body segments increased above neutrality values during the 15min exercise bout, and this increase in mean $T_{sk}$ is certainly taken into account when rating overall thermal sensation. Therefore, while changes in OS at rest can be interpreted as resulting from the local cooling only, the same cannot be said for OS during exercise. Although this may seem
logical, it seems important to point this out because as shown in Figure 3.18, ∆OS/∆Ts_k values during exercise are all either negative or close to 0, and it would be incorrect to assume a direct causal relationship between the decrease in Ts_k at the cooled segment and the increase in overall thermal sensation. Similarly to local thermal sensation, the “less cold” overall thermal sensation is a result of several factors. In this case, the increase in skin temperature at non-cooled body sites and the increase in internal body temperature are likely to explain the increase in overall thermal sensation during skin cooling at one body segment.

In addition to the temperature-related factors, a body of literature has suggested that neural and hormonal mechanisms occurring during exercise are likely to influence the response to both noxious and innocuous stimuli (refer to Koltyn, 2000 for a complete review). Evidence suggests that movement itself can lead to the reduction in transmission of the sensory information to the thalamus and somatosensory cortex. In the awake cat, evoked potentials recorded in response to radial nerve stimulation are reduced during movement of the limb (Coulter, 1974; Ghez & Pisa, 1972). Psychophysical experiments have also shown that the threshold for detecting cutaneous stimuli rises during active movement of the stimulated area (Coquery et al., 1971; Dyhre-Poulsen, 1978; Garland & Angel, 1974). The mechanism behind this is thought to be the attenuation or interruption of sensory information flow, because an action being performed such as movement renders it irrelevant or misleading (Rushton et al., 1981). This selection of information by the CNS results in the disregard of some of the afferent information gathered by the sense organs during active movement. It is therefore possible that the great reduction in thermal sensitivity to cold at the upper- and lower legs does not only reflect the increase in muscle temperature, but also this reduction in sensory flow caused by their movement during exercise.

Psychological factors may also play a role in the decreased thermal sensitivity to cold. It has been shown that high levels of arousal may decrease the response of thalamic neurons to the stimulation of skin in the monkey (Casey et al., 1993). Moreover, Bushnell et al. (1985) found that attention influenced noxious and
innocuous heat detection in humans and monkeys. Despite the low intensity of exercise used in the present study, arousal and attention may have also contributed to the decrease in thermal sensitivity to cold reflected by $\Delta LS/\Delta T_{sk}$ and $\Delta OS/\Delta T_{sk}$.

In the present study, thermal sensation slowly decreased after the end of exercise. After 15min of recovery, absolute local thermal sensation values were still significantly greater (i.e. less cold) than at the end of the resting period, despite skin temperature being significantly lower. When converted into $\Delta LS/\Delta T_{sk}$ the values were significantly lower (i.e. lower thermal sensitivity) at the end of the 15min recovery compared with rest. The thermal sensitivity values during recovery were around half way between resting and exercising, suggesting that it may have taken approximately another 15min for thermal sensitivity to be back to normal. These results are in agreement with the hypothesis that exercise-induced stress hormones might play a key role in the reduction of somatic sensitivity by dynamic exercise (Janal et al., 1984; Kemppainen et al., 1985; Pertovaara et al., 1984). The time course of the effects of dynamic exercise on thermal thresholds has been found to be similar to that of endocrine response with a long-lasting after effect (Kemppainen et al., 1985). The activation of the stress analgesia system (Lewis et al., 1984) was therefore deemed to be a possible mechanism to explain the modulation of somatosensory sensitivity. Additionally, it has been demonstrated by Kozyreva (2006) that the acute effects of noradrenaline iontophoresis include a reduction in the number of cold and warm spots on the skin without any change in skin temperature. It is commonly known that exercise induces the release of stress hormones including noradrenaline (e.g.: Floras et al., 1986) which take time to regain resting values after the end of exercise. It is therefore credible that the reduction in thermal sensitivity found in the present study reflects the exercise-induced increase in stress hormones levels.
3.4.3.2. Thermal comfort

The present results showed a radical change in local and overall thermal comfort during exercise, compared with resting values. Regarding overall thermal comfort, the values largely increased as soon as 5min after the onset of exercise. After 10min however, overall thermal comfort values started to decrease again in all cases. This decrease in overall thermal comfort should be interpreted with overall thermal sensation values in mind. Indeed, since overall sensation reached positive (warm) values, it is likely that thermal comfort values decreased as a result of feeling warm, despite the local cooling, in contrast to the discomfort caused by feeling cold at rest. This was confirmed in conversations with participants who confirmed that they started to feel “uncomfortably warm” by the end of the exercise phase. Most participants also mentioned that the thermal discomfort was not only due to warmth, but also to sweating. It is important to take into account thermal sensation values when interpreting thermal comfort values, because the deterioration of thermal comfort can either reflect individual feeling “too cold” or “too hot”. As shown in the present experiment, exercising at a low intensity for a short duration can alter the cause of a negative thermal comfort.

In contrast to overall thermal comfort, absolute values of local thermal comfort did not only increase significantly, but also went from negative (discomfort) to positive values by the end of the 15min exercise bout. This occurred while $T_{sk}$ continued dropping and with a minimal increase in core temperature. These results are in line with Marcus and Redman (1979) who found that exercise positively affected thermal comfort during hypothermia, even if core and skin temperature continued decreasing. Their protocol consisted of different levels of exercise intensity, and their results showed that thermal comfort was proportional to work rate up to the maximum level tested of 65% VO$_2$ max. It is well known that thermal comfort is affected by the thermal state of the body (Chatonnet & Cabanac, 1965; Mower, 1976; Attia and Engel, 1982; Nakamura et al., 2008). Cabanac (1969) defined thermal alliesthesia as the pleasure/displeasure sensation aroused by a given peripheral thermal stimulus, according to the internal thermal state of a subject. A
typical example is that the same hand warming produces a comfortable or uncomfortable feeling depending on whether the individual is hypothermic or hyperthermic. Exercise-induced alliesthesia is physiologically useful, as the metabolic heat produced by exercise will tend to restore thermal balance in an individual whose body heat stores are depleted. Thus a thermal stimulation is felt comfortable when it serves to regain normal body temperature, and felt uncomfortable when it worsens internal thermal conditions. Somehow, the central nervous system processes sensory input so that it is perceived as comfortable or uncomfortable depending on the thermal status of the body. Interestingly, the magnitude of this alteration in hedonic valence was found not to be uniform for all body areas. Participants reported the greatest level of local thermal comfort when cycling while their lower legs were being cooled, suggesting that cooling the area corresponding to the exercising muscles may be the best way of maximising local thermal comfort during exercise. It should however be noted that cooling the exercising muscles may not always be the best method for thermal strain alleviations, as it has been demonstrated by Price and Mather (2004) that during upper-body exercise, lower-body cooling is a more effective method for inducing favourable changes physiological and thermal strain than cooling the upper body.

3.4.4. Conclusions

The present study provides a comparison of thermal sensitivity to cold at 8 body segments, both in terms of terms of thermal sensation and thermal comfort. The data showed that the lower back, upper arms and upper legs are the most sensitive body segments at rest. In contrast, particularly low levels of thermal sensitivity were found at the abdomen and lower legs. These differences may reflect the existence of complex mechanism of integration at the CNS, which takes into account the surface area stimulated, the density of thermoreceptors present at each body segment, and the risk that skin cooling at that region will result in a core temperature decrease. To the best of our knowledge, this study is the first one to provide thermal sensitivities at whole body segments, which is relevant for
applications where the actual surface area stimulated must be taken into account. These results are applicable in several contexts such as the design of clothing and the improvement of thermal manikin models, in an effort to avoid skin temperature reductions in areas of the body which are particularly sensitive to cold, or by targeting these areas for maximal effect.

In response to the second research question, the present data demonstrate an important loss in thermal sensitivity to cold during exercise and post-exercise recovery, compared with resting values. While confirming the alliesthesial effect of exercise on thermal comfort during cooling, the present results also show that the intensity of local cold sensations is radically changed as a result of exercise. Several contributing factors to the decrease in sensitivity were discussed, including internal temperatures as well as neural, hormonal and psychological factors.

It must be noted that due to the criterion imposed for participants’ selection, results of the present study cannot be generalised to any individuals. While height should not affect the relative thermal sensitivities of body segments, the present results cannot be applied to females and/or individuals outside the 18 – 30 age range.
Chapter 4

Study 3: Body mapping of thermal sensitivity to cold in the upper body at rest and during exercise

4.1. Chapter summary

The current experiment aimed to explore inter- and intra-segmental differences in thermal sensitivity to cold, at rest and during light exercise. Fourteen male participants were tested at rest and whilst cycling at 30% VO$_2$ max. Sixteen body sites were stimulated in a balanced order, using a 25 cm$^2$ thermal probe (20, 25 and 30°C) applied onto the skin. Thermal sensations resulting from the stimuli were assessed using an 11-point cold sensation scale. Variations were found within body segments, particularly at the upper and lower abdomen where the lateral regions were significantly more sensitive than the medial areas. Furthermore, mean thermal sensations were significantly greater at rest than during exercise in all body sites except for the central chest, lateral upper back and posterior upper arm which only showed a trend. Neural and hormonal factors were considered as potential mechanisms behind this reduction in thermal sensitivity. The present data provides evidence that thermal sensitivity to cold varies within body segments, and it is significantly reduced in most areas during exercise.

4.2. Introduction

The term “body mapping” refers to the examination of regional differences across the human body for one specific parameter. With applications by designers and sports manufacturers in mind, research in this area has become increasingly popular, particularly in the physiology domain (e.g.: Havenith et al., 2008; Smith and Havenith, 2011). The results of chapter 3 demonstrated the existence of significant
differences in thermal sensitivity to cold between body segments. While this provides inter-segmental comparisons, little is known on whether the relative thermal sensitivity values found are representative for the whole segment, and how large variations within segments may be. Previous studies showed that vast variations exist within body segments for other thermal parameters such as sweating (Havenith et al., 2008; Smith & Havenith, 2011; Smith & Havenith, 2012). The next logical step in this project was to investigate whether thermal sensitivity to cold also differs within body segments. The first aim of the present study was therefore to create body maps of thermal sensitivity to cold, with a focus on intra-segmental comparisons within the 3 main upper body areas: front torso, back and arm.

In order to achieve this, a different experimental approach must be used regarding stimulus surface area. In studies 1 and 2, a water-perfused suit was used to cool the entire surface of each body segment in order to calculate thermal sensitivities of each segment regardless of their different surface areas. In the present study however, comparisons will be made between different locations within these segments. A much smaller thermal stimulus must therefore be used, and this must imperatively be of the same surface area for each stimulation, in order to make intra-segmental comparisons possible.

The effects of exercise on thermal sensitivity to cold will also be assessed in the present study. This may allow confirming or refuting the finding in study 2 that thermal sensitivity to cold is reduced during periods of exercise, compared to rest. Moreover, the relatively great number of locations tested will permit to identify any regional differences in the effects of exercise on thermal sensitivity to cold. The second aim of the present study was therefore to compare thermal sensitivity to cold at rest and during exercise in 16 body locations within the upper body.

Additionally, the relationship between local levels of body fat and thermal sensitivity to cold is poorly understood. In consequence, the third aim of the present study was to investigate correlations between local thermal sensation resulting from a cold stimulus and local skinfold thicknesses.
4.3. Methods

4.3.1. Participants

The study was advertised at Loughborough University via group emails and posters displayed around campus. The inclusion criterion were: being male, European (Caucasian), aged 18-30, and at least recreationally active, defined for the purpose of this study as performing physical activity for at least 2 hours per week. The age range was chosen due to the potential age effect on thermal sensitivity to cold (for a review see Guergova & Dufour, 2011), and the fitness level criterion was used to ensure that all participants were able to complete the test with no difficulties.

Fourteen healthy male participants aged 22.3 ± 3.1 years were recruited from the student population. They were sent a participants’ information sheet as in study 1 and 2, with a description of the tests, and asking to refrain from high intensity exercise and alcohol 24 hours prior to testing. They were also requested to abstain from caffeine and food consumption during the 2 hours prior to each session. Each participant was asked to come to the laboratory on three occasions, with at least two days between each test.

4.3.2. Pre-experimental session

All participants were required to attend the Environmental Ergonomics Research Centre at least two days prior to the first experimental session. Upon arrival at the laboratory, participants were given a detailed explanation on the testing procedures. They then completed a health questionnaire and provided informed consent. The pre-experimental session consisted of a series of anthropometric measurement, followed by a sub-maximal fitness test. The procedure followed and the tests carried out were identical to those described in chapter 2. Briefly, this first consisted of anthropometric measurements of height, body mass, and skinfold thicknesses. These were taken using the 7-point caliper method (Jackson and
Pollock, 1978) specific to the male population for calculation of body fat percentage (BF %). Maximal oxygen consumption (VO2max) was then deduced using a modified version of the Åstrand-Rhyming sub-maximal cycling test (1954), identical to that described in chapter 2. In preparation to the experimental sessions, participants were subsequently familiarised with the testing procedures. An habituation session was conducted, in which several body sites were stimulated with examples of strong and weak cold stimuli. In the second and third sessions, the thermal sensitivity test was performed at rest and during exercise, in a balanced order.

4.3.3. Experimental sessions

4.3.3.1. Equipment and experimental set-up

A series of pilot tests was performed prior to this study, in order to assess the possible experimental procedures. The thermal stimulator available for testing was a NTE-2 thermal sensitivity tester (Physitemp instruments Inc., USA), which consists of a temperature controller and temperature stimulator (Figure 4.1) as well as a water tank and pump unit. The stimulator has a Peltier element which cools down or warms up the stimulator, depending on the direction of the current. The water tank and pump are used to avoid overheating. The stimulator, also referred to as thermal probe, is a 5 x 5 cm metal block which can be set at temperatures ranging from 5 to 50°C. Its cooling or warming depends upon the applied current direction, which can be changed by one of the three controls situated on the temperature controller. The probe also encloses a temperature sensor which is directly connected to the digital readout of the temperature controller (Figure 4.1).
The cycle ergometer was positioned according to the handedness of the participant, in order for the body sites to be stimulated on the left hand side for right-handed participants and vice-versa. The thermal stimulator was placed on a working platform situated next to the cycle ergometer, and the digital display was hidden from the participant by a piece of opaque adhesive film.

The pilot tests drew attention to the difficulty of having to handle the thermal probe as well as write the thermal sensations down. In order to make this simpler and save time, it was decided to video record the tests using a Sony camcorder (DCR-SX60 HandyCam) set on a tripod placed approximately 1m away to the side of the participant.

4.3.3.2. Experimental Procedure

The laboratory methods for all experiments undertaken are described under a generic experimental protocol which was approved by Loughborough University ethical committee (Generic Protocol G10-P10). Upon arrival in the laboratory for the second and third sessions, participants changed into shorts, socks and trainers. The investigator marked each of the 16 testing sites on the skin using a washable marker. These were distributed across the upper body as follows: front torso = 6; upper limb = 4; back = 6 (Figure 4.2). All tested sites were medial or on the left

Figure 4.1 Thermal sensitivity tester (left) and its application onto the skin (right)
hand side of the body, assuming symmetry (e.g.: Claus et al., 1987; Meh and Denišlič, 1994). A detailed description of the body sites’ location can be found in Appendix 6. Measurements were done to the nearest 0.1cm using a 150cm non-elastic tape measure (Hoechstmass, Germany).

Figure 4.2 Name and location of the 16 body sites for the measurement of thermal sensitivity

Participants self-inserted a rectal thermometer (Grant Instruments, Cambridge, England) 10 cm beyond the rectal sphincter for measurement of core temperature ($T_c$). Four skin thermistors (Grant Instruments, Cambridge, England) were taped to the chest, upper arm, thigh and calf for calculation of mean skin temperature (mean $T_{sk}$) using Ramanathan’s weighing formula (1964). Skin and rectal temperature sensors were connected to an Eltek/Grant 10 bit, 1000 series data logger (Grant Instruments, Cambridge, England) recording temperature at 10 second-intervals.

After preparation, participants were taken to the laboratory ($T_a = 21.5 \pm 0.8^\circ C; RH = 44.2 \pm 4.8\%$). Room ambient temperature and relative humidity were measured using a Vaisala HMP35DGT sensor (Vaisala, Helsinki, Finland) and recorded at 1 minute intervals using an Eltek/Grant 10 bit, 1000 series squirrel data logger (Grant Instruments, Cambridge, England). They then sat on the cycle ergometer (Lode Excalibur, Groningen, Netherlands).
The initial part of the test consisted of a 20 minutes $T_c$ and mean $T_{sk}$ stabilisation period. During this period and the remainder of the experiment, participants either remained seated (rest condition), or cycled at 60 rpm with a workload corresponding to 30% of their predicted $VO_2\text{max}$ (exercise condition). This low intensity was selected in order to avoid any fatigue during the experiment and to limit the thermal changes to the body. The ergometer maintained work load levels stable regardless of small fluctuations in pedal frequency thanks to the built-in electrical control mechanism. In both conditions, another familiarisation to the thermal sensitivity test was performed during the temperature stabilisation period. This was done to ensure that all participants were thoroughly familiarised with the thermal sensitivity test prior to its commencement. The climatic conditions were chosen to provide a single temperature that would allow the body to be close to neutral at rest while not inducing a very high sweat rate during exercise.

At the end of the stabilisation period, the investigator started the camcorder and the thermal sensitivity test begun. Thermal sensitivity to cold was tested at each of the 16 body sites in a balanced order to prevent any order effects. The 25 cm$^2$ thermal sensitivity tester (NTE-2, Physitemp instruments Inc., USA) was placed directly onto the skin over the marked site, and participants were instructed to rate thermal sensation at 2 different times: immediately after contact with the probe (transient sensation) and after 10 seconds of stimulation (steady-state sensation). A thermal sensation scale for noxious heat stimulation (Casey and Morrow, 1984) was adapted for innocuous cold stimulation. In this scale, 0 indicated “not cold” and 10 “extremely cold”. After each steady-state sensation rating, the probe was removed from the skin and the site was re-warmed with a hand warmer (Dura-Warm, The Grange, UK) directly applied onto the skin for 10 seconds. This was however deemed unnecessary for the 30°C stimuli. This was done in an attempt to minimize the cooling effect of one site on the following site, especially if two adjacent sites were tested successively. A fresh hand warmer was activated at the start of each new set of tests.

After re-warming the skin, the experimenter moved on to the next body site. The test was repeated at the following 3 stimulus temperatures: 20, 25 and 30°C. All
sites were tested at one temperature before repeating the test at the next temperature. The order of stimulus temperature was counter-balanced to prevent any order effect.

Pressure was standardised by using the same experimenter in all tests. To avoid an effect of surprise on the transient cold sensations, a verbal warning of the location of each out-of-sight body site prior to stimulation (e.g.: “lateral lower back”). In the exercising condition, any sweat present was gently wiped off the skin before each stimulus using a towel. Distractions were minimised throughout the thermal sensitivity test. At the end of the exercise condition, the participant was given time to cool down. Temperature sensors were then removed and participants were allowed to leave, providing that their core temperature was below 38.5°C.

### 4.3.4. Data Analysis

Statistical analysis was performed using SPSS (Statistical Package for the Social Sciences, version 16.0, Chicago, USA). Mean $T_{sk}$ and $T_c$ at the end of the stabilisation period were compared between rest and exercise using paired-samples t-tests. Body maps of thermal sensations at rest and during exercise were developed based on the generally accepted assumption of left-right symmetry in thermal sensitivity (e.g.: Claus et al., 1987; Meh and Denišlič, 1994). Thermal sensations were analysed with a 4-way repeated measures ANOVA with stimulus temperature, body sites, conditions (rest/exercise) and times (transient/steady-state) as within subject factors. In order to identify any statistical differences in mean thermal sensations at individual sites between conditions, a series of paired-samples t-tests was completed. With 16 sites being compared between conditions, and over 100 possible comparisons between zones within subjects, multiple post-hoc comparisons are made with the risk of inflating type I error. This matter has been discussed in the literature (Bender and Lange, 1999; Perneger, 1998). Based on these discussions, it was decided that a Bonferroni would be overly conservative (pushing the limit P value for significance to 0.003 for body sites) for the present
type of exploratory study, and would dramatically inflate type II error. It was therefore decided to provide uncorrected $P$ values and bring to the reader’s attention that these should be interpreted with multiple comparisons in mind (Havenith et al., 2008). In addition, significance of comparisons which include Bonferroni corrections will also be reported, highlighting the strongest effects.

The relationship between local sensitivity and local fat levels was assessed for the upper body skinfold thickness measurement sites established in the literature. These were: chest, mid-axillary, abdominal, supra-iliac, biceps, triceps and subscapular which corresponded to body sites 2, 4, 5, 6, 7, 9 and 14, respectively. In particular, one Pearson’s $r$ correlation coefficient was produced for each body site between local skinfold thickness and the corresponding local thermal sensation. This was repeated for thermal sensations of all conditions, times and stimulus temperatures. This will be referred to as the between-subjects approach (Table 4.1). Finally, the effect of body fat on sensitivity to cold was also analysed between sites with a correlation between mean thermal sensations and the corresponding mean skinfold thickness. This will be referred to as the between-regions approach (Table 4.2).

Table 4.1 Example of data layout for the between-subjects approach of the correlation between thermal sensation and skinfold thicknesses (example of the chest)

<table>
<thead>
<tr>
<th>Participant number</th>
<th>Chest Skinfold</th>
<th>Chest Overall mean thermal sensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.1</td>
<td>4.5</td>
</tr>
<tr>
<td>2</td>
<td>10.7</td>
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<tr>
<td>3</td>
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<td>3.1</td>
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<td>14</td>
<td>6.9</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Table 4.2  Example of data layout for the between-regions approach of the relation between thermal sensation and skinfold thicknesses.

<table>
<thead>
<tr>
<th>Body Site</th>
<th>Mean Skinfold</th>
<th>Overall mean thermal sensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8.2</td>
<td>3.2</td>
</tr>
<tr>
<td>4</td>
<td>7.6</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>14.2</td>
<td>2.6</td>
</tr>
<tr>
<td>6</td>
<td>9.5</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>4.4</td>
<td>3.2</td>
</tr>
<tr>
<td>9</td>
<td>9.5</td>
<td>2.9</td>
</tr>
<tr>
<td>14</td>
<td>10.8</td>
<td>3.6</td>
</tr>
</tbody>
</table>

4.4. Results

4.4.1. Participants

Physical characteristics of the participants can be found in Table 4.3. The high standard deviations for the VO$_2$ max and body composition parameters can be explained by the fact that the recruitment process was done with very general inclusion criteria related to fitness level (at least 2 hours of exercise per week).

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Body Fat %</th>
<th>VO$_2$ max (ml·kg$^{-1}$·min$^{-1}$)</th>
<th>30% intensity (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>22.3</td>
<td>181.6</td>
<td>73.7</td>
<td>9.3</td>
<td>47.6</td>
</tr>
<tr>
<td>SD</td>
<td>3.1</td>
<td>6.2</td>
<td>10.3</td>
<td>3.6</td>
<td>9.7</td>
</tr>
</tbody>
</table>

4.4.2. Mean skin and core temperatures

Paired-samples t-tests showed a significant difference for T$_c$ (p < 0.001) whereas mean T$_sk$ was not significantly different between the two conditions (p = 0.081). Means and t-values are reported in Table 4.4.
Table 4.4  Mean skin temperature and core temperature in the two conditions. * indicates a significant difference between conditions (p<0.05)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mean $T_{sk}$ (°C)</th>
<th>$T_c$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>30.0 ± 0.7</td>
<td>37.1 ± 0.3</td>
</tr>
<tr>
<td>Exercise</td>
<td>30.4 ± 0.9</td>
<td>37.6 ± 0.2</td>
</tr>
<tr>
<td>t-value</td>
<td>1.19</td>
<td>-7.31*</td>
</tr>
</tbody>
</table>

4.4.3. Local thermal sensation

All thermal sensation means are listed in Table 4.5. The effects of stimulus temperature, body site, time and condition were analysed with a four-way repeated measures ANOVA. Mauchly’s test indicated that the assumption of sphericity had not been violated for any of the main effects (sites, conditions, times, temperatures). There was therefore no need for correction of degrees of freedom (Field, 2009).

4.4.3.1. Effect of stimulus temperature

*Main effect of temperature and interaction with body sites*

The mean thermal sensation values for all sites with the 20, 25 and 30°C were respectively 5.5, 3.9 and 0.3. The main effect of stimulus temperature was statistically significant, $F(2,26) = 239.07; p<0.0005$. An interaction effect was also found between stimulus temperature and body site, $F(2,26) = 4.44; p < 0.0005$. The differences in mean thermal sensations between the three temperatures are illustrated in Figure 4.3.
Table 4.5 Thermal sensations: all means and SD's. TR = transient; ST = steady-state

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean rest 20°C</th>
<th>SD</th>
<th>Mean rest 20°C</th>
<th>SD</th>
<th>Mean rest 20°C</th>
<th>SD</th>
<th>Mean rest 25°C</th>
<th>SD</th>
<th>Mean rest 25°C</th>
<th>SD</th>
<th>Mean rest 30°C</th>
<th>SD</th>
<th>Mean rest 30°C</th>
<th>SD</th>
<th>Mean rest 30°C</th>
<th>SD</th>
<th>Mean rest 30°C</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.3</td>
<td>1.3</td>
<td>5.3</td>
<td>1.8</td>
<td>5.5</td>
<td>1.5</td>
<td>4.2</td>
<td>1.8</td>
<td>4.7</td>
<td>1.3</td>
<td>3.6</td>
<td>1.4</td>
<td>3.9</td>
<td>1.9</td>
<td>2.2</td>
<td>1.8</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>7.0</td>
<td>1.4</td>
<td>6.1</td>
<td>1.9</td>
<td>5.4</td>
<td>1.7</td>
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<td>1.7</td>
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<td>3.7</td>
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<tr>
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<td>4.9</td>
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<td>1.9</td>
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<td>0.6</td>
<td>0.9</td>
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</tr>
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<td>4.9</td>
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<td>1.5</td>
<td>3.8</td>
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<td>3.6</td>
<td>1.5</td>
<td>3.6</td>
<td>1.5</td>
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<td>1.8</td>
<td>1.4</td>
<td>0.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Temperature comparisons

Mean thermal sensations resulting from the 20°C, 25°C and 30°C stimulus at all body sites are presented in Figure 4.4. The paired-samples t-tests indicated that all 16 sites showed significant differences between 20 and 30°C, between 20 and 25°C, and between 25 and 30°C which was still true after Bonferroni correction for multiple comparisons (p < 0.016).

Figure 4.3  Thermal cold sensation as a function of body site for all three stimulus temperatures, arranged from least to most sensitive at 20°C. The scale used for thermal sensation rating is 0 = not cold; 10 = extremely cold.
Figure 4.4 Mean thermal cold sensations. 20°C (A), 25°C (B) and 30°C (C) stimulus. Means across conditions and times (n = 14)
4.4.3.2. Effect of time (transient – steady-state)

**Main effect of time and interaction with body sites**

The transient thermal sensation was significantly greater (colder) than the steady-state thermal sensation, $F(1, 13) = 83.14, p<0.0005$. The mean difference in thermal sensation between the two times is 1.1 units. Additionally, a significant interaction was found between time and body site, $F(15, 195) = 8.11, p<0.0005$. Mean thermal sensations of all sites for both times are illustrated in Figure 4.5.

![Figure 4.5](image-url)

**Figure 4.5** Transient (1) and steady-state (2) mean thermal cold sensations for all body sites. The scale used for thermal sensation rating is 0 = not cold; 10 = extremely cold.
Time comparisons

Mean transient and steady-state thermal sensation values can be found in Figure 4.6.

Figure 4.6  Mean transient (A) and steady-state (B) local thermal cold sensations. Means across all conditions and stimulus temperatures (n = 14)
The t-tests indicated that in every individual body site, thermal sensation was significantly greater (colder) immediately after stimulus than after 10 seconds (p<0.0005), which remained significant in all body sites after Bonferroni correction. All differences are listed in Table 4.6.

<table>
<thead>
<tr>
<th>Body site</th>
<th>Mean difference</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest – central</td>
<td>0.9</td>
<td>6.8</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Chest – lateral</td>
<td>0.9</td>
<td>7.3</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Upper abdomen – central</td>
<td>1.1</td>
<td>7.7</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Upper abdomen – lateral</td>
<td>1.3</td>
<td>8.7</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Lower abdomen – central</td>
<td>0.8</td>
<td>5.4</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Lower abdomen – lateral</td>
<td>1.4</td>
<td>9.4</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Upper back – lateral</td>
<td>1.2</td>
<td>8.7</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Upper back – central</td>
<td>1.3</td>
<td>8.8</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Middle back – lateral</td>
<td>1.5</td>
<td>7.2</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Middle back – central</td>
<td>1.6</td>
<td>7.4</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Lower back – lateral</td>
<td>1.3</td>
<td>5.6</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Lower back – central</td>
<td>1.3</td>
<td>8.8</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Upper arm – anterior</td>
<td>1.0</td>
<td>14.0</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Upper arm – posterior</td>
<td>1.0</td>
<td>6.7</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Lower arm – anterior</td>
<td>0.8</td>
<td>4.7</td>
<td>&lt; 0.0005#</td>
</tr>
<tr>
<td>Lower arm – posterior</td>
<td>0.6</td>
<td>6.3</td>
<td>&lt; 0.0005#</td>
</tr>
</tbody>
</table>

4.4.3.3. Effect of body location

Main effect of body location

The ANOVA revealed a significant main effect of body site, F(15, 195) = 14.60, p<0.0005. Mean thermal sensations across all conditions, times and stimulus temperatures are presented in Figure 4.7.
Regional comparisons

A total of twenty-nine significant differences were found. Noticeably, the lateral upper abdomen and lateral lower abdomen were significantly greater than eleven and ten other sites, respectively. On the other hand, the posterior lower arm had a thermal sensation significantly smaller than ten other sites in total. All the significant differences between sites are listed in Table 4.7. Intra-segmental differences are denoted with a (*).
Table 4.7 List of significant differences between sites. (*) denotes intra-segmental differences

<table>
<thead>
<tr>
<th>Site A</th>
<th>Site B</th>
<th>Mean difference (A-B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central chest</td>
<td>Lateral upper abdomen (*)</td>
<td>-0.9</td>
</tr>
<tr>
<td></td>
<td>Lateral lower abdomen (*)</td>
<td>-0.9</td>
</tr>
<tr>
<td>Lateral chest</td>
<td>Lateral upper abdomen (*)</td>
<td>-0.8</td>
</tr>
<tr>
<td></td>
<td>Lateral lower abdomen (*)</td>
<td>-0.8</td>
</tr>
<tr>
<td></td>
<td>Posterior lower arm</td>
<td>0.8</td>
</tr>
<tr>
<td>Central upper abdomen</td>
<td>Lateral upper abdomen (*)</td>
<td>-0.8</td>
</tr>
<tr>
<td></td>
<td>Lateral lower abdomen (*)</td>
<td>-0.8</td>
</tr>
<tr>
<td></td>
<td>Posterior lower arm</td>
<td>0.8</td>
</tr>
<tr>
<td>Lateral upper abdomen</td>
<td>Central lower abdomen (*)</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>Central upper back</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Lateral lower back</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Central lower back</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Anterior upper arm</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Posterior upper arm</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>Anterior lower arm</td>
<td>1.0</td>
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<tr>
<td></td>
<td>Posterior lower arm</td>
<td>1.6</td>
</tr>
<tr>
<td>Central lower abdomen</td>
<td>Lateral lower abdomen (*)</td>
<td>-1.4</td>
</tr>
<tr>
<td>Lateral lower abdomen</td>
<td>Lateral lower back</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Central lower back</td>
<td>0.9</td>
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<tr>
<td></td>
<td>Anterior upper arm</td>
<td>0.8</td>
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<tr>
<td></td>
<td>Anterior lower arm</td>
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<td>Posterior lower arm</td>
<td>1.6</td>
</tr>
<tr>
<td>Lateral upper back</td>
<td>Posterior lower arm</td>
<td>0.9</td>
</tr>
<tr>
<td>Central upper back</td>
<td>Posterior lower arm</td>
<td>0.9</td>
</tr>
<tr>
<td>Lateral middle back</td>
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</tr>
<tr>
<td>Central middle back</td>
<td>Posterior lower arm</td>
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</tr>
<tr>
<td>Central lower back</td>
<td>Posterior lower arm</td>
<td>0.7</td>
</tr>
<tr>
<td>Anterior upper arm</td>
<td>Posterior lower arm (*)</td>
<td>0.8</td>
</tr>
</tbody>
</table>

4.4.3.4. Effect of experimental condition (rest – exercise)

**Main effect of condition and interaction with body sites**

Participants gave higher (colder) ratings of thermal sensation in the resting condition compared to exercise, as revealed by the ANOVA, $F(1, 13) = 10.29$, $p = 0.007$, with a mean difference of 0.9 units in thermal sensation. Additionally, an significant interaction effect was found between condition and body site, $F(15, 195)$
\[ = 1.85, p = 0.031. \] Mean thermal sensations of all sites for both conditions are illustrated in Figure 4.8.

Figure 4.8 Mean thermal cold sensations at rest (Condition 1) and during exercise (Condition 2) for all body sites. The scale used for thermal sensation rating is 0 = not cold; 10 = extremely cold.

**Condition comparisons**

Mean values for thermal sensation at rest and exercise can be found in Figure 4.9.
Mean thermal sensation was significantly greater at rest than during exercise (p<0.05) in all body sites except for the central chest, lateral upper back and posterior upper arm which only showed a trend (0.05 < p < 0.1). After Bonferroni correction for multiple comparisons however, only two body sites were still significantly different between conditions (p < 0.0031). These were the lateral chest and lateral middle back. All the differences are listed in Table 4.8.

Figure 4.9  Mean local thermal cold sensations during rest (A) and exercise (B). Mean across all times and stimuli temperatures (n = 14).
Table 4.8  Significance levels of the rest-exercise comparison analysed with paired-samples t-tests.  *Trend before Bonferroni correction.  ‡ Significant difference before Bonferroni correction. # Significant difference after Bonferroni correction.

<table>
<thead>
<tr>
<th>Body site</th>
<th>Mean difference</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest – lateral</td>
<td>1.2</td>
<td>4.5</td>
<td>0.001 ‡#</td>
</tr>
<tr>
<td>Chest - central</td>
<td>0.7</td>
<td>2.3</td>
<td>0.069*</td>
</tr>
<tr>
<td>Upper abdomen – central</td>
<td>1.0</td>
<td>2.9</td>
<td>0.013 ‡</td>
</tr>
<tr>
<td>Upper abdomen – lateral</td>
<td>1.3</td>
<td>3.3</td>
<td>0.006 ‡</td>
</tr>
<tr>
<td>Lower abdomen – central</td>
<td>0.7</td>
<td>2.3</td>
<td>0.042 ‡</td>
</tr>
<tr>
<td>Lower abdomen – lateral</td>
<td>1.2</td>
<td>2.7</td>
<td>0.018 ‡</td>
</tr>
<tr>
<td>Upper back – lateral</td>
<td>0.8</td>
<td>1.9</td>
<td>0.075*</td>
</tr>
<tr>
<td>Upper back – central</td>
<td>1.0</td>
<td>2.9</td>
<td>0.013 ‡</td>
</tr>
<tr>
<td>Middle back – lateral</td>
<td>1.1</td>
<td>3.6</td>
<td>0.003 ‡</td>
</tr>
<tr>
<td>Middle back – central</td>
<td>0.9</td>
<td>2.8</td>
<td>0.015 ‡</td>
</tr>
<tr>
<td>Lower back – lateral</td>
<td>0.8</td>
<td>2.7</td>
<td>0.018 ‡</td>
</tr>
<tr>
<td>Lower back – central</td>
<td>1.1</td>
<td>2.8</td>
<td>0.016 ‡</td>
</tr>
<tr>
<td>Upper arm – anterior</td>
<td>0.9</td>
<td>3.3</td>
<td>0.006 ‡</td>
</tr>
<tr>
<td>Upper arm – posterior</td>
<td>0.5</td>
<td>2.1</td>
<td>0.054*</td>
</tr>
<tr>
<td>Lower arm – anterior</td>
<td>1.0</td>
<td>3.3</td>
<td>0.005 ‡</td>
</tr>
<tr>
<td>Lower arm – posterior</td>
<td>0.5</td>
<td>2.5</td>
<td>0.027 ‡</td>
</tr>
</tbody>
</table>

4.4.4. Relationship between thermal sensitivity and body fat levels

4.4.4.1. Between-subjects approach

The skinfold thicknesses of each participant are listed in Appendix 7. A significant negative relationship was found between mean thermal sensations and the corresponding skinfold thicknesses at two body sites: biceps (r = -0.66; p<0.05) and triceps (r = -0.55; p<0.05). Although not statistically significant, the chest showed a trend towards a negative correlation (r = -0.48; p=0.08). All the correlations can be found in Table 4.9.

Table 4.9  Correlations between mean thermal sensation (across all temperatures, conditions and times) and skinfold thicknesses at the corresponding site. *Indicates p<0.05

<table>
<thead>
<tr>
<th>Body Site</th>
<th>r coefficient</th>
<th>p -value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest</td>
<td>-0.48</td>
<td>0.08</td>
</tr>
<tr>
<td>Mid-axillary</td>
<td>-0.11</td>
<td>0.71</td>
</tr>
<tr>
<td>Abdominal</td>
<td>-0.34</td>
<td>0.24</td>
</tr>
<tr>
<td>Suprالiliar</td>
<td>0.13</td>
<td>0.67</td>
</tr>
<tr>
<td>Subscapular</td>
<td>-0.32</td>
<td>0.26</td>
</tr>
<tr>
<td>Biceps</td>
<td>-0.66</td>
<td>0.01*</td>
</tr>
<tr>
<td>Triceps</td>
<td>-0.55</td>
<td>0.04*</td>
</tr>
</tbody>
</table>
4.4.4.2. Between-regions approach

No significant correlation was found between mean thermal sensations across all temperatures, conditions and times and mean local skinfold thicknesses ($r = -0.36; p = 0.430$).

4.5. Discussion

4.5.1. Thermal sensitivity: importance of terminology

As highlighted in the introduction chapter, previous investigators have used various methodologies and protocols for the measurement of what they all referred to as thermal sensitivity. It is essential to distinguish and define what other studies have measured, as well as what was measured in the present study. Sensory cold spots body mapping is effectively an indirect quantification of the density of thermal receptors, using a fixed stimulus intensity and asking the participant to state whether the stimulus was perceived or not. This method therefore uses a measure of thermal detectability which can be defined in this case as the ability to identify the existence of a supra-threshold thermal stimulus. This method has previously been used to explore the distribution of thermal sensitivity across the body (e.g.: Rein, 1925; Strughold and Porz, 1931). Moreover, using the methods of limits, Lee et al. (2010a) specified that a body region which requires a smaller rise or fall in the temperature to detect cool or warm thermal sensations is considered as thermally sensitive. In this case thermal sensitivity is thus also a measurement of detectability and can be defined as the ability to identify a change in stimulus temperature.

The two latter methods involve the use of thermal stimuli just under or equal to the perceptual thermal threshold. In contrast, methods of thermal intensity rating use suprathreshold thermal stimuli. This procedure consists of asking the participants to rate the intensity of the thermal sensation they perceive. The difference between the two types of methods (i.e. detectability and intensity rating) is important to highlight because they do not provide the same measurement.
Indeed, threshold detection involves solely the identification of the existence of a thermal stimulus, whereas intensity rating requires a more complex judgment of the level of cold perceived. Not establishing these differences would inevitably lead to erroneous comparisons between data collected with different methods. For example, the forehead was considered as the most sensitive area to cold by Lee et al. (2010a) who used the method of limits, while Stevens (1979) has found it to be the least sensitive to cold using an intensity rating method. In the present study, a thermal sensitive body site is defined as one associated with a strong (cold) thermal sensation intensity resulting from a constant stimulus temperature.

4.5.2. Mechanisms for the transient and steady-state thermal sensations

Previous investigations have demonstrated the initial overshoot of thermal receptors via the analysis of their discharge pattern by dissection, isolation and stimulation of cold fibres (e.g.: Braun et al., 1980; Schäfer et al., 1988). Other researchers have also shown the evolution of thermal sensation over time with a conductive or convective stimulus covering all or most of a body segment (e.g. Arens et al., 2006). Similarly, the evolution of thermal sensation and comfort with a convective whole-body stimulus have also been investigated before (e.g.: deDear et al., 1993; Arens et al., 2006). However, to the best of our knowledge, this study is the first to demonstrate a drop in the intensity of thermal sensation between initial contact with the skin and a few seconds later. This significant decrease found between transient (immediate) and steady-state (after 10 sec) cold sensations reflects thermoreceptors’ dynamic properties. Indeed, it has been demonstrated that cold fibres initially respond with an overshoot in impulse frequency when subjected to an abrupt change in temperature, which is followed by a rapid fading in their activity (Braun et al., 1980; Schäfer et al., 1988). Hensel et al. (1960) investigated the impulse frequency of individual cold fibres when cooling cat’s skin, and found that the overshoot only lasted for around 1 second, after which it
dropped and reached an almost steady state after around 2 seconds of stimulation (Figure 4.10)

However, it has been suggested that the length of adaptation to a cold stimulus increases with the surface area of the stimulator (Jenkins, 1937). In the present study, the transient to steady-state time duration was chosen after pilot experiments revealing that thermal sensation stabilised after 10 seconds of stimulation. It is likely that the duration needed for complete adaptation would be different with a stimulus of a different size or temperature. It would be of great interest for future work to systematically investigate the effects of spatial summation on overshoot duration.
4.5.3. Mechanisms for regional differences in thermal sensitivity

4.5.3.1. Intra-segmental comparisons (within body segments)

As illustrated in Figure 4.7, the most sensitive areas were the lateral upper abdomen and lateral lower abdomen. Mean thermal sensations in these two sites were significantly greater than other sites within the front torso, including both sites of the chest and the central abdomen sites. To the best knowledge of the author, this high thermal sensitivity of the lateral abdomen, compared to other areas of the front torso has not been established before. No significant differences were found between body sites at the back. Regarding the arms, no significant differences were present between the anterior and posterior sites at the upper arm or forearm, but the posterior forearm was significantly less sensitive than the upper arm sites.

Among the variables that have been suggested as causes of regional differences in thermal sensitivity, are the uneven distribution of cutaneous thermoreceptors and the existence of a weighing of thermoafferent information by the integration centre in the central nervous system (Burke and Mekjavić, 1991). Unfortunately, previous cold spot body mapping studies did not compare lateral and medial areas within the front torso or the back, and therefore little is known on the relative distribution of thermoreceptors on different areas of these body segments. It would be of great interest to investigate cold spots densities in those areas in future experiments. The results on the arms are in line with Choi and Seol (2001) who found a greater density of cold spots on the upper arm compared with the forearm.

Another factor which may explain the differences in thermal sensitivity between body sites is the rate of change in skin temperature (Δ $T_{sk}$ rate). Indeed, it is well established that different areas of the body lose their heat content more readily than others. Nakamura et al. (2008) found that applying the same cold stimulus at different areas of the skin resulted in different levels of Δ $T_{sk}$, and suggested that these regional differences in heat loss are likely caused by differences in skin blood
flow due to vasomotor status and tissue vascularity. Moreover, Li and colleagues (2005) found that the lateral chest and lateral abdomen are subjected to the greatest $\Delta T_{sk}$ rates when individually exposed to a 20°C ambient air temperature while the rest of the body is covered. Although the present stimulus is much more dominant in defining the $T_{sk}$ drop than Li and colleagues’ air exposure, $\Delta T_{sk}$ rates may explain some of the variations shown in thermal sensitivity.

Furthermore, hair density on the abdominal regions may also be a contributing factor in the regional differences found. Researchers have consistently found that innocuous and noxious thermal sensitivities depend on skin type. Electrophysiological recordings from primates (Duclaux and Kenshalo, 1980) and evoked potentials studies (Treede et al., 1995; Granovsky et al., 2005) suggest that glabrous and hairy skin may differ in the population of thermal receptors. Furthermore, several authors observed differences in thermal sensitivity to warmth between the two skin types (Stevens and Choo, 1998; Towell et al., 1996; Iannetti et al., 2006). Even more relevant to the protocol used in the present study is the fact that hair may act as an insulator for the skin and introduce thermal resistance between the stimulus and the skin. During the 1960’s and early 1970’s, Setty focused his research on body hair patterns and published a total of 13 articles on this subject. One paper describes the varieties of abdominal hair patterns of Caucasian males (Setty, 1967). Using visual observation and photographs inspection of 700 adult male participants, Setty depicted a total of 22 different abdominal hair patterns, 3 of which had a much greater incidence than the others (Figure 4.11).
These illustrations show that the most common varieties of abdominal hair patterns in Caucasian males consist of hairy central abdominal regions in comparison to lateral areas. This corresponds well with the distribution of thermal sensitivity found on the abdomen. Although participants in the present study were not particularly hairy, the possibility that variations in abdominal thermal sensitivity are linked to levels of hairiness cannot be excluded. Moreover, a trend of difference in thermal sensation was found between the posterior and anterior forearm (p = 0.096). Mean thermal sensation was 0.6 units colder at the inner forearm than on the dorsal side of the segment. These results are consistent with the hypothesis that body hair density and thermal sensitivity may be closely related, since the dorsal forearm is more hairy than its inner part (Setty, 1964). Although the potential effect of body hair density may have been removed by shaving participants at each body site tested, this would have affected participants’ natural thermal sensitivity to cold. Since it is intended to apply the present results for clothing design, removing the natural insulation provided by body hair in some areas of the body would not be appropriate in the present project. This would however be an interesting approach for future work.

In order to better understand the mechanisms behind this strong thermal sensitivity to cold at the lateral abdomen, future studies should answer the following two questions:
- How does the cold spot distribution compare between lateral and central parts of the abdomen?
- What is the role of body hair density in thermal sensitivity to cold?

The latter research question will be approached further in this thesis.

4.5.3.2. Inter-segmental comparisons (between body segments)

Results of the present study are in agreement with Stevens’ (1979) data to some extent. Indeed, the lower back and upper back regions are more sensitive to cold than the chest and central abdomen. Although the low sensitivity of the lower arm and forearm were inconsistent with Stevens’ results, it was in line with Lee and Tamura’s results (1995) who found that these two areas are the least sensitive. The distribution of thermal sensitivity is however less comparable with studies using the methods of limits (e.g.: Lee et al., 2010a) and cold spots mapping (e.g.: Choi et al., 2001). This may be due to different methodologies providing a measurement of different aspects of thermal sensitivity, as explained earlier in the discussion. Moreover, it has been suggested that the response of a single thermoreceptor measured with the spots density method might be below the threshold of conscious sensation, whereas a larger area may have led to thermal sensations because of spatial summation (Hensel, 1981).

Comparing the present results with the thermal sensitivity results of study 2 is not straightforward, due to the difference in thermal stimulus surface area and method. For example, the stimulus was applied to both upper arms in study 2, which may explain why they appeared as relatively more sensitive compared with other body segments in study 2, according to the principle of spatial summation of afferents activity (Stevens, 1979). In the present study however, the stimulus was of a unique surface area which revokes any spatial summation effect. Regarding comparisons of torso body segments, dissimilarities were found in the present study compared with study 2. The present results expand the knowledge on regional thermal sensitivity to cold, by highlighting that differences between body segments
highlighted in study 2 and in previous research are unavoidably influenced by intra-segmental differences.

For example, the relatively low thermal sensitivity found at the abdomen in study 2 is only in partial agreement with the present results. Indeed, while the central area of the abdomen was the least sensitive in the current results, the lateral regions were also towards the most sensitive compared with other sites. The overall thermal sensitivity to cold found at the abdomen in study 2 may thus reflect the spatial summation of all areas of this segment. The same is also partially true for the lateral mid-back, which showed a high level of thermal sensitivity to cold in the present study, while the central region did not. When cooling the lower back in study 2, central and lateral regions of the lower and mid-back were simultaneously cooled, resulting in a relatively great thermal sensitivity at the lower back. Thus, the present results confirm the hypothesis made in chapter 3 that thermal sensitivity to cold at whole body segments is influenced by a non-uniform sensitivity within segments. This means that the actual number of cold spots for each segment may be very different from those presented by Strughold and Porz' (1931), who only used one measuring point per body segment.

4.5.4. Mechanisms for the effects of exercise on thermal sensitivity

Despite the low intensity of exercise, thermal sensitivity was lower in all of the 16 body sites tested, and this was significant in all body sites except for the central chest, lateral upper back, and anterior upper arm sites where only a trend towards significance was found. Although the Bonferroni correction diminished the number of sites significantly different between conditions, the consistent effects of exercise on thermal sensation throughout the body is unquestionable. These results are in line with those found in chapter 3, as well as with Kemppainen et al. (1985) who found an increase in the temperature change needed to evoke cool and warm sensations during exercise, compared to resting values. The present results also suggest that the distribution of changes in thermal sensitivity during exercise is not
constant across the upper body, with some sites displaying almost no change while others showed large changes in sensation. This resulted in a more homogenous body map during exercise than at rest, especially at the arms and the back.

One logical explanation for the changes in sensitivity could be found in $T_{sk}$. Indeed, a decrease in $T_{sk}$ in exercise would result in thermoreceptors being stimulated with a smaller $\Delta T_{sk}$, which would decrease the impulse frequency and in turn reduce the intensity of a thermal sensation. This was confirmed in several studies looking at the effects of skin temperature on warm and cool thresholds (Hirosawa et al., 1984; Lele, 1954). This could only have affected the transient cold sensation results in the present study as for the steady state value only the final $T_{sk}$ should be relevant. However, no significant change was found in mean $T_{sk}$ during exercise; In fact, a trend was found towards a higher mean $T_{sk}$ during exercise ($p = 0.081$), which should result in colder thermal sensations according to the theoretical dynamics of thermoreceptors activity explained above. This suggests that $T_{sk}$ is unlikely to be the mechanism behind the reduction in thermal sensitivity. Furthermore, although the present results suggests that a causal relationship may exist between the increase in $T_c$ (0.5°C) and the decrease in thermal sensitivity, previous results suggest that this may not be the case. In particular, Mower (1976) found that fluctuations in $T_c$ achieved passively in a bath have an effect on the pleasantness of a thermal stimulus, but not on its intensity. This suggests that the decrease in cold sensation intensity found in the present study is likely to be the result of another physiological change occurring during exercise.

A body of literature has suggested that neural and hormonal mechanisms occurring during exercise are likely to influence the response to both noxious and innocuous stimuli; refer to Koltyn (2000) for a complete review. As discussed in chapter 3, evidence suggests that movement itself can lead to the reduction in transmission of the sensory information to the thalamus and somatosensory cortex. In the awake cat, evoked potentials recorded in response to radial nerve stimulation are reduced during movement of the limb (Coulter, 1974; Ghez, 1972). Psychophysical experiments have also shown that the threshold for detecting cutaneous stimuli rises during active movement of the stimulated area (Coquery et al., 1971; Dyhre-
Poulsen, 1978; Garland and Angel, 1974). The mechanism behind this is thought to be the attenuation or interruption of sensory information flow, because an action being performed such as movement renders it irrelevant or misleading (Rushton et al., 1981). This selection of information by the central nervous system results in the disregard of some of the afferent information gathered by the sense organs during active movement. Although all the tested sites were on the upper body, it is possible that this effect of movement also plays a role on static body regions.

Regarding the hormonal mechanisms, it has been proposed that exercise-induced stress hormones might play a key role in the reduction of somatic sensitivity by dynamic exercise (Janal et al., 1984; Kemppainen et al., 1985; Pertovaara et al., 1984). The time course of the effects of dynamic exercise on thermal thresholds has been found to be similar to that of endocrine response with a long-lasting after effect (Kemppainen et al., 1985). The activation of the stress analgesia system (Lewis et al., 1984) was therefore deemed to be a possible mechanism to explain the modulation of somatosensory sensitivity. Additionally, it has been demonstrated by Kozyreva (2006) that the acute effects of noradrenaline iontophoresis include a reduction in the number of cold and warm spots on the skin without any change in skin temperature. It is commonly known that exercise induces the release of stress hormones including noradrenaline (e.g.: Floras et al., 1986) and it is therefore credible that the reduction in thermal sensitivity found in the present study reflects the exercise-induced increase in stress hormones levels.

Finally, psychological factors may also play a role in the decreased thermal sensitivity to cold. It has been shown that high levels of arousal may decrease the response of thalamic neurons to the stimulation of skin in the monkey (Casey et al., 1993). Moreover, Bushnell et al. (1985) found that attention influenced noxious and innocuous heat detection in humans and monkeys. Despite the low intensity of exercise used, arousal and attention may have also contributed to the decrease in thermal sensitivity to cold found in the current study.
4.5.5. Effects of skinfold thicknesses on thermal sensitivity

The analysis of the relation of local thermal sensations and local skinfold thicknesses for each individual body site on its own (between-subjects approach) revealed two significant negative correlations. These were found at the biceps and triceps. These may indicate that larger subcutaneous fat layers at these sites are associated with a lower thermal sensitivity to a cold stimulus. As explained in the introduction, the main rationale for investigating the relationship between thermal sensitivity and skinfold thicknesses is that fluctuations in fat layers has been shown to influence skin temperature. More specifically, body areas with higher levels of fat tend to show lower skin temperatures (Leblanc, 1954; Livingstone et al., 1987; Frim et al., 1990; Claessens-van Ooijen et al., 2006). Since a lower local $T_{sk}$ would result in a lower $\Delta T$ between $T_{sk}$ and the stimulus temperature (for a cold stimulus), this may reduce the sensation of cold, as thermoreceptors react to a change in $T_{sk}$ (Hensel, 1982). Another potential explanation is that the stimulus may result in a larger $\Delta T_{sk}$ in an area with greater fat levels, as with more fat less heat will come from inside the body to the skin. Finally, one last rationale for the potential role of body fat is related to the basic function of temperature sensation, which is to drive an individual to search for the appropriate thermal environment, in order to avoid changes in internal temperature. It seems coherent that low temperatures in the body regions with greater levels of fat may be less sensitive to cold, because they constitute a low “risk” of internal cooling thanks to the insulating role of subcutaneous fat.

It must also be noted that body fat thicknesses do not account for all the regional variations found in skinfold thicknesses. Indeed, the latter is a measurement of both the layer of subcutaneous fat and the skin thickness. Several authors have suggested that the thickness of skin may impact thermal sensitivity (Stoll, 1977; Golja and Mekjavić, 2005; Guergova and Dufour, 2011). Indeed, it has been demonstrated that the latency of the thermoreceptors’ response depends on its position in the skin (Bligh et al., 1990; Becser et al., 1998). Epidermal thickness is almost constant over the body, 60 to 100 microns, except for the palm and sole.
where the stratum corneum part of the epidermis alone can reach 600 microns in thickness. In contrast, dermal thicknesses have a large variation in most body areas (Rushmer et al., 1966).

In contrast to these between-subjects effects at 2 sites, the between-regions (within subjects) approach showed no significant correlation between mean local skinfold thickness and mean thermal sensation at the corresponding site. This suggests that variations in skinfold thickness between sites may not play a key role in the regional distribution of thermal sensitivity to cold. Other factors described earlier in the discussion are therefore thought to play a more major role in explaining the variation in sensitivity to cold between body regions.

4.5.6. Conclusions

In conclusion, results of the present study based on thermal intensity ratings provide new insights and knowledge on thermal sensitivity to cold as measured by thermal intensity rating in response to a constant cold stimulus. Future research was suggested, in order to verify new hypotheses proposed in the present study. Specifically, the following aims were studied and discussed:

4.5.6.1. Comparison of the transient and steady-state responses to cold

The present results showed a consistent reduction in cold thermal sensation between initial contact and after 10 seconds of stimulation. This drop in intensity of sensation is attributed to the main dynamic properties of thermoreceptors, namely that a cold receptor responds with an overshoot of its discharge on sudden cooling (Hensel, 1982).
4.5.6.2. **Comparison of thermal sensitivity to cold at 16 different body sites within the torso, back and arm**

Mean thermal sensations were determined for each body site. The most sensitive areas were the lateral abdomen, whereas the least sensitive ones were the forearms and the middle of the abdomen (umbilical region). More importantly, significant differences were found within segments. Indeed, the lateral areas of the abdomen (upper and lower) were significantly more sensitive to cold than their central regions. Additionally, the posterior forearm was significantly less sensitive than the upper arm sites. Physical and physiological characteristics from which the regional differences may have stemmed were discussed. These were:

- distribution of thermoreceptors
- existence of a weighing of thermoafferent information between different fibres
- distribution of hair density
- local body fat levels
- distribution of skin thickness

4.5.6.3. **Comparison of thermal sensitivity to cold at rest and during exercise**

Results of the present study indicate that physical exercise produces a reduction in thermal sensitivity to innocuous cold stimuli, as measured by the intensity rating of a 25 cm² stimulus of 20, 25 and 30°C. The following mechanisms which may have contributed to this decreased sensitivity were discussed:

- Change in local skin temperature
- Change in core temperature
- Reduction in the transmission of sensory information to the thalamus and somatosensory cortex associated with one of the following:
  - Movement
  - Reduction in attention
Increase in arousal
- Activation stress-induced analgesia mechanisms:
  ➔ Release of stress hormones

It is likely that a combination of several of these factors has contributed to the reduced thermal sensitivity found in the present study.

4.5.6.4. Analysis of the relationship between local skinfolds and thermal sensitivity

The results indicated that significant negative correlations exist between mean local thermal sensation and local skinfold thickness at the biceps and triceps. This suggests that larger subcutaneous fat layers are associated with a lower thermal sensitivity to a cold stimulus at these body areas. However, no significant correlations were found between mean thermal sensation and mean local skinfold thickness when comparing different sites over the body. This suggests that body fat layers do not play a role as important as other parameters (e.g. thermoreceptors density) in the determination of regional differences in thermal sensitivity.

4.5.7. Limitations

The author acknowledges some experimental limitations in the present study, related to the cold stimulus application. Firstly, the pressure with which the probe was applied onto the skin was not controlled or measured, since the equipment available did not include this feature. Although thermal probe pressure has not been systematically investigated, some authors have attempted to control for it when designing their apparatus when measuring thermal thresholds (Bertelsmann et al., 1985; Jamal et al., 1985; Jamal et al., 1986). Despite the effort to hold the probe with a constant pressure in the present study, the pressure with which it was applied onto the skin may have varied slightly. Previous studies have used a
handheld thermal probe applied directly on the skin (e.g. Levy et al., 1989; Sheffield et al., 2000), and it has been suggested that controlling pressure in thermal sensory testing is not imperative (Levy et al., 1989), but it must be recognised that pressure directly affects cooling speed (Havenith et al., 1992).

Secondly, participants’ sweat in the exercising condition may have slightly influenced the subjective data. Indeed, sweat may have influenced conductivity of the stimulus on the skin. A better conduction of the stimulus would however be expected to induce a stronger response (colder sensation) instead of the observed reduction. In an attempt to minimize this limitation, sweat was gently wiped off just before applying the stimulus.
Chapter 5

Study 4: Upper and lower body distribution of thermal sensitivity to cold – The effects of ethnicity

5.1. Chapter summary

This chapter explores thermal sensitivity to cold at rest in 3 groups of individuals from different ethnic backgrounds all currently living in the UK. A total of 29 participants were recruited: 10 Caucasians from Great Britain, 10 Asians from China, and 9 Africans from Nigeria. Thermal sensitivity to cold was tested at 27 body sites with a 20°C thermal probe, and participants reported their local cold sensation. Photos of the participants’ front torso, arms, back and legs were then taken, and local hairiness density was rated at 9 sites using a 5-point scale (0 to 4). Body maps of cold sensation were created and revealed that areas of high thermal sensitivity included the lateral abdomen in all groups, the medial lower back in the Chinese group, and the medial upper abdomen in the Nigerian group. Regarding comparisons between ethnicities, the results showed significant differences and tendencies towards significance at several body sites. Most differences found were between the British and the Chinese group, with colder sensations reported by Chinese participants. The results also showed some dissimilarity between the groups in the distribution of thermal sensitivity across the body. The possibility that the greater body hair density found in the British group is one of the factors making them less sensitive to cold was suggested.
5.2. Introduction

The influence of ethnicity on thermoregulation and sensory functions has been widely investigated by scientists and anthropologists over the past decades. Differences between individuals from various origins are thought to be a result of adaptations to their environment. For example, Meehan (1955) demonstrated that the mean skin temperature of the fingers during ice water immersion was highest for Alaskan natives, followed by Caucasians and Africans, respectively. Iampietro et al. (1959) showed that Africans and Caucasians reacted similarly to whole-body cold exposure, but that Africans had a reduced hunting reaction to local cold exposure. Yoshimura and Iida (1952) observed that the “resistance frostbite index” was higher for populations living in cold areas, such as Chinese, Mongol and Orogon people, than for the Japanese. Elsner (1963) showed that foot temperatures were higher in Australian aboriginals and Andean Indians when compared to Caucasians during cold exposure.

Additionally, several studies have investigated differences between Caucasians and African-Americans. Adams and Covino (1958) reported that when exposed to the cold, African-Americans fail to increase heat production as soon as, or as high as Caucasians or Eskimos. Furthermore, a more recent study by Farnell et al. (2008) showed that Caucasians expend more energy to maintain a higher rectal temperature compared with their African-American counterparts, and maintain a higher $T_c$ at the end of a 120 min exposure to a 10°C environment. It was concluded that this “hyper” metabolic heat production group may prove to be beneficial in the maintenance of rectal temperature and ultimately temperature homeostasis over a prolonged period during recovery from cold stress, thereby lowering the risk of hypothermia in Caucasians compared to African-American individuals. Regarding sensitivity, research has been previously done on ethnic differences in response to thermal noxious stimuli. Edwards and colleagues (1999) compared thermal pain thresholds and thermal pain tolerance in European Americans and African Americans. Although no group differences emerged for thermal pain thresholds, African Americans demonstrated lower thermal pain tolerance than European
Americans. In contrast, Watson et al. (2005) did not find any differences in thermal pain responses between South Asian and White British healthy males.

Previous research has also investigated other types of noxious stimuli (e.g.: Woodrow et al., 1972; Campbell et al., 2004; Gazerani and Arendt-Nielsen, 2005; Komiyama et al., 2007). However the effects of innocuous stimuli have been given much less interest. Lee and colleagues (2010a) investigated regional differences in thermal thresholds (temperature at which warmth/cold is initially sensed) between individuals of different origins and demonstrated that tropical natives from Malaysia were less sensitive to detect warmth at the forehead than temperate natives from Japan. Specifically, Malaysian males detected warmth at a stimulus temperature 0.9°C higher than Japanese males, despite there being no differences in resting $T_{sk}$. The authors suggested that the forehead is a specific body site that reflects the level of heat acclimatization in cutaneous thermal thresholds, resulting from being exposed at all times. It was also concluded that the less sensitive perception to warmth of tropical natives seems to be advantageous in respect to withstanding heat stress with less feelings of discomfort and a greater ability to work in hot climates. To the best of our knowledge, no study has used an intensity rating method (how strong is the feeling of warmth or cold) to compare thermal sensitivity between individuals of different ethnicities. The aim of the present study was therefore to investigate whether differences exist in the levels and regional distribution of thermal sensitivity to cold between individuals of three different ethnic backgrounds, at rest. For the present study, the three groups to be compared were British, Chinese and Nigerian, all residents in the UK.
5.3. Methods

5.3.1. Participants

Participants were recruited from the Loughborough University student population via emails and posters. They were asked to read the participant information sheet similar to that in Appendix 1, which informed them about the purpose and aim of the study and details of the study requirements. Participants were requested to avoid strenuous exercise and alcohol for 24 hours prior to the study, and to abstain from caffeine and food consumption during the 2 hours prior to each session. They were also asked to fill out a health questionnaire (Appendix 2) as well as answer a series of questions to ensure that they fit the following inclusion criteria:

1. The participant must be male, not older than 35 and born in China, GB or Nigeria
2. Both parents must be born in the same country as the participant
3. British participants must be self-identified as “Caucasian British”
4. All participants must have lived in Great Britain at least for the last 6 months
5. The participant should have a reasonable understanding of the English language
6. The participant should not have a neurological condition that might affect cold perception

Criterion number 4 was to ensure that all participants were acclimated to the same (British) climate, and criterion number 5 was to make sure that all participants understood the thermal sensitivity test and more specifically the thermal sensation scale. A total of 33 participants were initially recruited, but after inspection of the questionnaires, 4 participants had to be excluded from the study. The remaining 29 participants included: 10 Caucasians from Great Britain, 10 Asians from China, and 9 Black Africans from Nigeria.
5.3.2. Procedures

Participants only needed to attend the laboratory on one occasion. Informed consent was provided, and all procedures were in accordance with the generic protocol G10-P10 which was accepted by the Loughborough University Ethical Advisory Committee prior to the start of the study.

Upon arrival at the laboratory, the participants were given a detailed explanation on the testing procedures. They then completed a health questionnaire, provided informed consent, and changed into their own shorts, socks and trainers.

The following anthropometric measurements were then taken: height, weight, and skinfolds thicknesses. These were taken using the 7-point calliper method (Jackson and Pollock, 1978) specific to a male population for calculation of body fat percentage. Participants were subsequently familiarised with the testing procedures. They were given a detailed description of the procedures, and participants practiced to rate their thermal cold sensation while stimuli of different temperatures were applied on their skin at various body sites. Participants verbally rated their thermal cold sensation immediately after contact with the probe (transient sensation), as well as 10 seconds after (steady-state sensation).

They were then asked to lie on a medical bench while the investigator marked each of the 28 testing sites on their skin. These were on the face and neck (4), front torso (6), back (6), arm and hand (6), leg and foot (5). A dot of approximately 1 cm diameter was drawn in the middle of the stimulus site. Measurements were done to the nearest 0.1 cm using a 150 cm non-elastic tape measure (Hoechstmass, Germany).

Pre-test body mass was then recorded using a calibrated Mettler ID1 Multirange electronic scale (Mettler Toledo, Leicester, UK; resolution= 0.001 kg). Four skin thermistors (Grant Instruments, Cambridge, England) were attached with Transpore surgical tape (3M Healthcare, USA) to the upper arm, chest, thigh and calf for measurement of $T_{sk}$ and calculation of mean $T_{sk}$ using Ramanathan’s weighing formula (Ramanathan, 1964). Skin temperature sensors were plugged onto an
Eltek/Grant 10 bit, 1000 series data logger (Grant Instruments, Cambridge, England) recording temperature at 2 second-intervals.

After preparation, participants were taken to the laboratory ($T_a = 21^\circ$C; $R_h = 40\%$) where they sat on the stool placed next to the testing apparatus. Room ambient temperature and relative humidity were measured using a Vaisala HMP35DGT sensor (Vaisala, Helsinki, Finland) and recorded at 1 minute intervals using an Eltek/Grant 10 bit, 1000 series squirrel data logger (Grant Instruments, Cambridge, England).

The initial part of the test consisted of a 10 minutes $T_c$ and $T_{sk}$ stabilisation period during which participants remained seated. A series of practice tests consisting of cold stimulus applications and thermal cold sensation ratings were done during the temperature stabilisation period, identical to the practice session done during the pre-experimental test session. This was done to ensure that all participants were thoroughly familiarised with thermal sensitivity test prior to the thermal sensitivity test commencement.

Prior to the start of the test, $T_c$ was measured with an oral thermometer (Vicks V911; Kaz Inc., MA, USA). Also, a reference temperature was measured on a black mat surface with the non-contact IR thermometer (Fluke 566, Washington, USA) with emissivity set at 0.98. A calibrated thermistor was taped to the black mat surface to allow correction of the $T_{sk}$ IR thermometer measurement. $T_{sk}$ was then measured at the stimulus site with the IR thermometer held approximately 30cm from the skin. Once $T_{sk}$ had been recorded, the 25 cm$^2$ thermal sensitivity tester (NTE-2, Physitemp instruments Inc., USA) set at 20°C was placed directly onto the skin over the marked site. This was done by the same experimenter for all the tests, and although there was no systematic control of the force with which the probe was applied possible, an attempt was made to keep it constant throughout the study. Participants verbally rated their thermal sensation on the thermal cold sensation scale for innocuous cold stimuli, on which 0 indicates “not cold” and 10 “extremely cold”. Thermal sensation was reported immediately after contact between the probe and the skin (“transient”) as well as after 10 seconds of stimulus
(“steady-state”). Time between initial contact with the skin and asking for the participant to rate his sensation again was measured with a stop watch constantly in sight of the investigator. To avoid an effect of surprise on the initial thermal cold sensation, the location of the site of stimulation was given as a warning prior to stimulus of each out-of-sight body site (e.g., “lateral lower back”). The site was then re-warmed with a hand warmer for 15 seconds, and the process was started again with the following body site. All 27 sites were tested in a balanced order. Once all 27 body sites had been stimulated at rest, both the $T_c$ measurement and the black mat surface temperature measurements were repeated. The 27 body sites location and their names are presented in Figure 5.1.

![Figure 5.1 Name and location of the 27 body sites tested](image)

At the end of the experiment, photos of participants’ arm, back, chest and leg were taken for analysis of body hair density.
5.3.3. Data analysis

For an easier visual comparison of thermal sensation at different body sites, body maps of sensitivity were developed with a scale consisting of 8 levels with a different colour being attributed to each level. This was done based on the assumption that no differences exist between left- and right-hand side of the body (e.g.: Claus et al., 1987; Meh and Denišlič, 1994).

Pre-stimulus $T_{sk}$ was corrected according to the difference found between the temperature indicated by the calibrated thermistor and the IR thermometer. Differences in pre-stimulus $T_{sk}$ were then analysed with a multivariate ANOVA (ethnicity * body site).

A separate Mixed Design ANOVA was performed for the transient and steady-state sensation, with body site (27 levels) as within-subject factors, and ethnicity (3 levels) as between-subject factor. The effect of ethnicity on thermal sensation at each body site was analysed with a Mixed Design ANOVA with ethnicity as a between-subjects factor. The data was then corrected for multiple comparisons using Bonferroni corrections. With 27 sites being compared between 3 ethnicities and therefore 81 possible comparisons between ethnicities, multiple post-hoc comparisons are made with the risk of inflating type I error. This matter has been discussed in the literature (Bender and Lange, 1999; Perneger, 1998). Based on these discussions, it was decided that a Bonferroni would be overly conservative (pushing the limit P value for significance to 0.0006 for ethnicities) for the present type of exploratory study, and would dramatically inflate type II error. It was therefore decided to provide the significant differences and trends ($0.05 \leq p \leq 0.1$) before correction for multiple comparisons and bring to the reader’s attention that these should be interpreted with multiple comparisons in mind (Havenith et al., 2008). In addition, significant differences after Bonferroni corrections for the multiple groups will also be reported, highlighting the strongest effects.

For the calculation of BF%, body density was first calculated with Jackson and Pollock’s equation (1978). Different equations were then used to calculate BF% for
each of the ethnicities; Siri’s equation (1956) was used for British, whereas BF% of the Chinese and Nigerian participants were calculated with Durnin and Womersley’s equations (1974) for Japanese and African American populations, respectively. Although not perfectly corresponding to the participants tested in the present study, the latter two equations were deemed more appropriate than the general equations normally used. The effect of body fat on sensitivity to cold was analysed with Pearson’s r correlation coefficients. For the 7 sites for which skinfold thicknesses were taken, a between-subjects approach and a between-regions approach were adopted for the analysis of the effects of body fat on sensitivity to cold, with in both cases the production of Pearson’s r correlation coefficients.

Finally, levels of local hairiness were estimated at the lower arm, upper arm, back, lateral abdomen, central abdomen, lateral chest, central chest, upper leg, and lower leg. This was done by evaluating the photos taken and rating each area using a 5-point scale (0 to 4), such that a score of 0 = the absence of hairs, a score of 1 = minimally evident hair growth and a score of 4 = extensive hair growth. From this an overall rating per participant was calculated as well, by simply adding all the local hairiness ratings. This method was initially developed by Garn (1951) and since became one of the most common methods for hair density estimation (Yildiz et al., 2010). Local thermal sensations were correlated with Local levels of hairiness, with both a within-subjects approach and a between-subjects approach at the following 9 body sites: lower and upper arm, back, lateral and medial abdomen, lateral and medial chest, lower and upper leg. Mean thermal sensations of several body sites were used for the abdomen and back areas.

Statistical analysis was performed using IBM SPSS Statistics (version 19.0, Chicago, USA). Differences in participants’ characteristics in each ethnic group were analysed using an ANOVA. The level of statistical significance was set at p < 0.05 for all statistical tests.
5.3. Results

5.3.1. Participants’ characteristics

Participants of the Caucasian group were significantly younger and taller than the Nigerian group. Their BF % was also significantly lower than the Nigerians’. No significant differences existed between the other groups (Table 5.1). No significant difference existed in Tc between the groups.

Table 5.1 Participants’ characteristics in study A. *p < 0.05 with British group.

<table>
<thead>
<tr>
<th></th>
<th>British (n=10)</th>
<th>Chinese (n=10)</th>
<th>Nigerian (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>23.0 ± 3.6</td>
<td>23.7 ± 1.9</td>
<td>28.1 ± 5.3 (*)</td>
</tr>
<tr>
<td>Residence in UK (months)</td>
<td>N/A</td>
<td>20.3 ± 11.8</td>
<td>23.2 ± 20.2</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.81 ± 0.08</td>
<td>1.79 ± 0.04</td>
<td>1.73 ± 0.06 (*)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>73.9 ± 8.1</td>
<td>70.2 ± 8.1</td>
<td>72.1 ± 11.8</td>
</tr>
<tr>
<td>%BF</td>
<td>7.4 ± 2.1</td>
<td>11.3 ± 3.8</td>
<td>12.8 ± 5.0 (*)</td>
</tr>
<tr>
<td>Σ 7 skinfolds (mm)</td>
<td>60.3 ± 10.3</td>
<td>84.2 ± 25.5</td>
<td>69.6 ± 38.4</td>
</tr>
<tr>
<td>Tc (°C)</td>
<td>37.2 ± 0.3</td>
<td>37.1 ± 0.2</td>
<td>37.1 ± 0.2</td>
</tr>
</tbody>
</table>

5.3.2. Skin temperature

Local Tsk values are presented in Figure 5.2. The ANCOVA for thermal sensation at each body site showed that Tsk was a significant covariant only at one body site (lateral anterior neck) out of the 27 sites tested. This weak effect of pre-stimulus Tsk on thermal sensation was confirmed by absence of a correlation between Tsk and transient (r = 0.039, p = 0.289) and steady-state (r = 0.044, p = 0.224) thermal sensations.

Mauchly’s sphericity test revealed a violation of sphericity. After Greenhouse-Geisser correction, The ANOVA showed a significant main effect of body site on pre-stimulus Tsk, F(2, 57) = 19.57; p < 0.0005. No significant main effect of ethnicity on pre-stimulus Tsk was found, F(2, 26) = 1.62; p = 0.216. The post-hoc analysis did not reveal any significant differences or tendencies among the groups. Finally, no significant interaction effect (body site * ethnicity) on pre-stimulus Tsk was found, F(4, 57) = 0.729; p = 0.589.
Figure 5.2 Pre-stimulus $T_{sk}$ at each body site (means of each ethnic group)
5.3.3. Thermal sensation

5.3.3.1. Transient thermal sensation

Mauchly’s sphericity test revealed a violation of sphericity. After Greenhouse-Geisser correction, the Mixed ANOVA revealed no significant main effect of ethnicity, $F(2, 26) = 0.271; p = 0.764$. Pairwise comparisons showed no significant difference between British and Chinese ($p = 0.493$), British and Nigerians ($p = 0.901$) or Chinese and Nigerians ($p = 0.586$). In contrast, a significant main effect of body site was found, $F(8, 198) = 12.33; p < 0.0005$ but no significant site * ethnicity interaction effect was found, $F(15, 198) = 0.90; p = 0.563$.

5.3.3.2. Steady-state thermal sensations

Mauchly’s sphericity test revealed a violation of sphericity. After Greenhouse-Geisser correction, the Mixed ANOVA revealed no main effect of ethnicity, $F(2, 26) = 1.94; p = 0.164$. However, the pairwise comparisons showed a strong trend towards significance between the British and Chinese groups, with Chinese participants reporting a thermal sensation 1.2 units colder than their British counterparts ($p = 0.063$). No significant difference was however found between British and Nigerians ($p = 0.234$) or Chinese and Nigerians ($p = 0.505$). Moreover, a significant main effect of body site was found, $F(8, 213) = 9.04; p < 0.0005$ but no significant site * ethnicity interaction effect was found, $F(16, 213) = 0.96; p = 0.503$. 
5.3.3.3. **Ethnicity effect at individual body sites**

The pairwise comparisons of the ANOVA with transient thermal sensations showed only 3 significant differences and trends before Bonferroni corrections. However, a total of 13 significant differences and trends were found amongst ethnicities before Bonferroni corrections for the steady-state thermal sensations. Most of these were between the British and the Chinese group, with a greater (colder) thermal sensation found in the Chinese group. Only one significant difference remained after Bonferroni correction for multiple comparisons. The significant differences and trends are presented in Table 5.2.

**Table 5.2** Significant differences and trends (0.05 ≤ p ≤ 0.1) between ethnicities. *Trend before Bonferroni correction. * Significant difference before Bonferroni correction. # Significant difference after Bonferroni correction.

<table>
<thead>
<tr>
<th>Body site</th>
<th>Transient (T) or Steady-State (SS)</th>
<th>Ethnicity A</th>
<th>Ethnicity B</th>
<th>Mean Difference (A - B)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 - Central upper abdomen</td>
<td>T</td>
<td>British</td>
<td>Nigerian</td>
<td>-1.5</td>
<td>0.097*</td>
</tr>
<tr>
<td>6 - Central upper abdomen</td>
<td>SS</td>
<td>British</td>
<td>Chinese</td>
<td>-1.5</td>
<td>0.080*</td>
</tr>
<tr>
<td>6 - Central upper abdomen</td>
<td>SS</td>
<td>British</td>
<td>Nigerian</td>
<td>-1.7</td>
<td>0.052*</td>
</tr>
<tr>
<td>7 - Lateral upper abdomen</td>
<td>SS</td>
<td>British</td>
<td>Chinese</td>
<td>-1.6</td>
<td>0.076*</td>
</tr>
<tr>
<td>8 - Central lower abdomen</td>
<td>SS</td>
<td>British</td>
<td>Chinese</td>
<td>-1.6</td>
<td>0.077*</td>
</tr>
<tr>
<td>10 - Upper arm - anterior</td>
<td>SS</td>
<td>British</td>
<td>Chinese</td>
<td>-1.7</td>
<td>0.019γ</td>
</tr>
<tr>
<td>12 - Palmar hand</td>
<td>SS</td>
<td>British</td>
<td>Chinese</td>
<td>-2.0</td>
<td>0.075*</td>
</tr>
<tr>
<td>13 - Anterior middle thigh</td>
<td>SS</td>
<td>British</td>
<td>Chinese</td>
<td>-2.0</td>
<td>0.027γ</td>
</tr>
<tr>
<td>15 - Dorsal foot</td>
<td>SS</td>
<td>British</td>
<td>Chinese</td>
<td>-2.3</td>
<td>0.019γ</td>
</tr>
<tr>
<td>15 - Dorsal foot</td>
<td>SS</td>
<td>British</td>
<td>Nigerian</td>
<td>-2.4</td>
<td>0.017γ</td>
</tr>
<tr>
<td>20 - Central middle back</td>
<td>SS</td>
<td>British</td>
<td>Chinese</td>
<td>-1.5</td>
<td>0.041γ</td>
</tr>
<tr>
<td>21 - Lateral lower back</td>
<td>SS</td>
<td>British</td>
<td>Chinese</td>
<td>-1.5</td>
<td>0.054*</td>
</tr>
<tr>
<td>22 - Central lower back</td>
<td>T</td>
<td>British</td>
<td>Chinese</td>
<td>-1.5</td>
<td>0.047γ</td>
</tr>
<tr>
<td>22 - Central lower back</td>
<td>T</td>
<td>Chinese</td>
<td>Nigerian</td>
<td>1.5</td>
<td>0.047γ</td>
</tr>
<tr>
<td>22 - Central lower back</td>
<td>SS</td>
<td>British</td>
<td>Chinese</td>
<td>-2.0</td>
<td>0.005#</td>
</tr>
<tr>
<td>26 - Posterior middle thigh</td>
<td>SS</td>
<td>British</td>
<td>Chinese</td>
<td>-1.5</td>
<td>0.086*</td>
</tr>
</tbody>
</table>

Due to the different levels of significance between ethnicities in transient and steady-state sensations, it was decided to present both transient and steady-state thermal sensitivity body maps for each ethnicity (Figure 5.3).
Figure 5.3 A&B  Mean values of thermal sensation at each body site for each ethnicity.  S-S denotes thermal sensations during steady-state (after 10 seconds of stimulus).
Figure 5.3 C&D  Mean values of thermal sensation at each body site for each ethnicity. S-S denotes thermal sensations during steady-state (after 10 seconds of stimulus).
Figure 5.3 E&F  Mean values of thermal sensation at each body site for each ethnicity. S-S denotes thermal sensations during steady-state (after 10 seconds of stimulus).
5.3.4. Skinfold thicknesses

No significant correlation was found in the between-subject analysis of the effects of skinfold thicknesses on thermal sensation (Table 5.3) or in the between-regions analysis ($r = 0.052; p = 0.447$).

<table>
<thead>
<tr>
<th>Body site</th>
<th>R value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest</td>
<td>-0.078</td>
<td>0.344</td>
</tr>
<tr>
<td>Triceps</td>
<td>0.204</td>
<td>0.144</td>
</tr>
<tr>
<td>Biceps</td>
<td>0.096</td>
<td>0.309</td>
</tr>
<tr>
<td>Abdominal</td>
<td>0.218</td>
<td>0.128</td>
</tr>
<tr>
<td>Midaxillary</td>
<td>-0.010</td>
<td>0.479</td>
</tr>
<tr>
<td>Suprailliac</td>
<td>-0.018</td>
<td>0.463</td>
</tr>
<tr>
<td>Subscapular</td>
<td>0.239</td>
<td>0.106</td>
</tr>
<tr>
<td>Quadriceps</td>
<td>0.240</td>
<td>0.105</td>
</tr>
<tr>
<td>Calf</td>
<td>0.096</td>
<td>0.310</td>
</tr>
</tbody>
</table>

5.3.5. Local density of hair

Individual values of hairiness are listed in Appendix 8. Mean total hairiness, calculated as the sum of 9 hairiness ratings for each person, was $13.2 \pm 5.0$ in the British group, $6.2 \pm 3.6$ in the Chinese group and $2.3 \pm 2$ in the Nigerian group. This was significantly greater in British than in Chinese ($p = 0.001$) and Nigerians ($p < 0.0005$). No significant difference existed between the Chinese and Nigerian groups. Figure 5.4 shows the front torso of a British, Chinese and Nigerian participant with hairiness values corresponding to their respective group’s mean value.
No significant correlation was found in the between-subject analysis of the effects of local hairiness on thermal sensation (Table 5.4).

### Table 5.4 Between-subjects analysis of the relationship between local hairiness level and local thermal sensation

<table>
<thead>
<tr>
<th>Body site</th>
<th>R value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower arm</td>
<td>-0.219</td>
<td>0.127</td>
</tr>
<tr>
<td>Upper arm</td>
<td>0.178</td>
<td>0.178</td>
</tr>
<tr>
<td>Back</td>
<td>-0.076</td>
<td>0.347</td>
</tr>
<tr>
<td>Lateral abdomen</td>
<td>0.001</td>
<td>0.497</td>
</tr>
<tr>
<td>Medial abdomen</td>
<td>-0.115</td>
<td>0.277</td>
</tr>
<tr>
<td>Lateral chest</td>
<td>-0.202</td>
<td>0.146</td>
</tr>
<tr>
<td>Medial chest</td>
<td>-0.136</td>
<td>0.242</td>
</tr>
<tr>
<td>Lower leg</td>
<td>-0.182</td>
<td>0.172</td>
</tr>
<tr>
<td>Upper leg</td>
<td>0.109</td>
<td>0.287</td>
</tr>
</tbody>
</table>

However, a significant negative correlation between mean local hairiness levels and mean local sensations was found when looking at all the sites together (r = -0.59; p = 0.048), indicating that regions of the body with lower levels of local hairiness were associated with greater (colder) local thermal sensations. It must be noted however that this significant correlation was largely influenced by the lower leg point (Figure 5.5), as removing this point results in the correlation not being significant anymore (r = -0.37; p = 0.185).
5.4. Discussion

Despite the numerous studies existing on ethnic difference in several aspects of thermoregulation and pain sensitivity, very little is currently known on whether thermal sensitivity to cold differs between individuals of different origins. The current study therefore aimed to investigate thermal sensitivity across the body, in 3 groups of individuals from different ethnic backgrounds. Similarly to study 3, a thermally sensitive body site was defined as one with a stronger thermal cold sensation score in response to the 20°C thermal stimulus.

The first observation on the present data is the consistency found in the distribution of thermal sensitivity over the upper-body, when compared with data from study 3. Indeed, the body maps presented in Figure 5.3 confirm the great sensitivity to cold at the lateral upper- and lower abdomen, as well as in the lateral mid-back region in the British participants. Similarly, the present results are consistent with the low levels of thermal sensitivity to cold found in study 3 at the central abdomen body site as well as the posterior lower arm. In addition to these the present study also provides local thermal sensitivities of
lower body regions as well as extremities, highlighting a relatively high sensitivity to cold on the posterior thigh, while the hands and dorsal foot showed particularly low levels of thermal sensitivity to cold.

Regarding ethnicities, the current results showed limited differences in thermal sensitivity between British, Chinese, and Nigerian individuals. A trend was found between British and Chinese in the steady-state, with Chinese being more sensitive than British as a main effect ($p = 0.063$). Furthermore, thermal sensations were found to be significantly colder in the Chinese group than the British before Bonferroni correction in several body sites. After Bonferroni corrections however, the difference between ethnicities remained significant at only one body site. This may be explained by a small sample and low statistical power. Stronger differences may have been found if the experiments were carried out on a larger sample of each tested population. Given the exploratory nature of the study, pre-Bonferroni results were considered relevant (Havenith et al., 2008).

In the present study, participants were selected not only based on their ethnicity, but also ensuring that all of them were currently living in the UK. Two reasons exist for such a selection. The first one is related to the obvious complexity of conducting research on autochthonous individual living in their own country, both in terms of costs and logistics. The second reason is related to acclimatisation, defined as short term adaptations to a new climate. Testing participants of different origins but all living in the same country has the advantage of reducing the chances for potential differences to be due to acclimatisation, since all participants tested in the present study should in theory be acclimatised to the British climate. This therefore increases the chances for any potential difference to be due to neurological and physiological changes which humans underwent as an adaptation to the diverse and sometimes extreme environmental conditions. These factors are discussed separately in the next sections.

5.4.1. Neurological factors

The idea that thermal sensitivity may vary between humans of different geographical origins has been suggested before. For example, the extinct Fueguian tribes of South America were
known to tolerate freezing conditions with minimal thermal protection. It is widely believed that selective forces within these populations favoured extraordinary cold tolerance (Hernandez et al., 1997). Another example is the prehistoric Polynesians who, similarly to the Fueguians, lived in a cool and wet marine environment. Visser and Dias (1999) examined skulls of two prehistoric Polynesian groups from New Zealand, the Moriori and Maori, and of one contemporary Indian group. They analysed the sensory nerve dimensions, based on the area of cranial nerve foramina. These features are of interest, because the cross-sectional area of a nerve is directly proportional to the number of axons and hence the number sensory receptors represented. Comparisons showed significantly lower cranial cutaneous sensory nerve foramina size in the prehistoric Polynesian groups, compared with the contemporary Indian group. This was interpreted as a lower facial cutaneous sensory nerve supply in the Polynesians. The authors proposed that reduced skin sensory nerve supply may have been selected as an adaptation to a cool and wet environment.

Although such anatomical analyses are way beyond the scope of the present study, the lower thermal sensitivity found in the British group may be partly linked to similar neural adaptations. Indeed, extremities are interesting body areas in terms of thermal sensitivity, because they have been and still are very often exposed to the environment, while the trunk, arms, and legs are covered with clothing (Lee et al., 2010a). The greater thermal sensitivity to cold found in these normally exposed areas for the Chinese and Nigerian groups are somewhat in line with Lee et al. (2010a) who found that the foreheads of tropical natives from Malaysia are less sensitive to warmth than those of temperate natives from Japan. It is widely accepted that European populations have been undergoing a greater level of cold stress than African populations. The same is only partially true for Chinese populations, as China’s climate varies greatly throughout the year and depending on the area of the country. Participants in the present study came from different cities, including some southern areas (mild climate) and some northern ones (cooler climate). The fact that the British group was less sensitive to cold than the Nigerian and Chinese groups at the dorsal foot may be related to such adaptations to a colder environment. Interestingly however, the forehead did not display large differences amongst ethnicities in the present study, thus not reproducing Lee’s results for the cold.
5.4.2. Physiological factors

Acute physiological adaptations as a consequence of the environment in which humans live have been widely studied, resulting in a body of knowledge on this research topic. On the other hand, evolutionary adaptations resulting from environmental factors are much more complex to investigate systematically, mainly because the adaptations cannot be witnessed in the same way as acute changes. This inevitably leads to speculative explanations about the exact cause behind differences found between various ethnic groups. Moreover, inter-racial comparisons require the assessment of independent participants, therefore involving a high risk of finding differences due to other factors than evolutionary adaptations. Despite this, research has explored several physiological characteristics which differ between ethnic groups and may result from environmental factors. These include adaptations in body mass, body shape and surface area, cranial morphology, skin colour, body composition and metabolic rate, and peripheral vasoconstriction. See Lambert et al. (2008) for a complete review.

As explained in previous studies, fluctuations in pre-stimulus $T_{sk}$ effectively result in a different $\Delta T_{sk}$ with which thermoreceptors are stimulated. Pre-stimulus $T_{sk}$ is therefore expected to have an effect on thermal sensation resulting from a given thermal stimulus, especially on the transient (initial) thermal sensation. In the present study the differences in pre-stimulus $T_{sk}$ between the groups were non-significant, low in magnitude ($< 1^\circ C$; see Figure 5.2), and much lower than the natural variations in $T_{sk}$ across the body (Figure 5.2). Moreover, the analysis also suggested that pre-stimulus $T_{sk}$ was a weak predictor of both transient and steady-state thermal sensation, as highlighted by a low slope regression line ($r^2 = 0.001$ and 0.002 respectively). This suggests that fluctuations in $T_{sk}$ may not be as influential as other physiological factors in thermal sensitivity.

Another factor which may explain the thermal sensation differences found between ethnicities in the present study is the density of body hair. No study had previously systematically compared body hair density amongst individuals of different ethnic background. Despite the small sample used, the present results confirm the widespread notion that European individuals have a greater body hair density than their Asian and African counterparts. More importantly, the significantly higher body hair density found in
British corresponds well with their lower thermal sensitivity, compared to the Chinese group. However, the Nigerians also had a significant lower body hair level than the British, but their thermal sensitivity was not significantly lower than that of the British group, suggesting that other factors may play a more important role in defining differences in sensitivity between the groups. Subcutaneous fat and skin thickness may be factors influencing thermal sensitivity. In the present study, no significant correlation was found between local skinfold thicknesses and local thermal sensation. However, the Nigerian and Chinese groups had greater mean sums of skinfold thicknesses the British group, although this difference was non-significant. It is possible that the Nigerian and Chinese groups would have appeared more sensitive if they had matched the British for sum of skinfold thicknesses.

In humans, hair mainly has an insulation role and therefore serves to protect from the cold (Johnson et al., 1993). It seems reasonable to suggest that in the present experiment, hair may have acted as an insulator for the skin, introducing thermal resistance between the stimulus (thermal probe) and the skin. This is in agreement with the significant correlation found in the cold sensation versus body hair density analysis, indicating that body regions with lower levels of local hairiness were associated with greater (colder) local thermal sensations (Figure 5.5) though this association may be flawed and based on a single data point. According to Hooton (1946), the loss of body hair in man must have taken place in a tropical climate, since such an adaptation is unlikely to take place in a cold environment. Other theories suggest that the loss of hairy covering in man is associated with an increase in subcutaneous fat layers. According to Keith (1912), humanisation, which resulted in a richer variety and a more ample command of food all year round, may be one of the reasons for the loss in human body hair. Indeed, such an improvement in pre- and post-natal nutrition may have brought about the increase in fat deposition, which in turn may have rendered body hair less needed, since a subcutaneous fat layer similarly preserves the warmth of the body (Hooton, 1946). This may have thus triggered the body hair loss which distinguishes humans from the other primates. Given the fact that regional fat distribution is known to vary with ethnicity (Rush et al., 2007), those people indigenous to cold climates may be expected to have developed a thick insulating layer of subcutaneous fat to offer optimal protection against the cold elements. Indeed, it has been reported that lean
subjects elicit an increase in heat production three times greater than their overweight counterparts, in response to exposure to even mild cold (Claessens-van Ooijen et al., 2006). Although this energy-efficient, “blunted” cold response in fatter individuals may appear beneficial, little evidence exists to suggest that those people indigenous to cold climates were able to accumulate particularly high levels of subcutaneous fat (Lambert et al., 2008). To the contrary, individuals living in cold climates often have skinfold thicknesses lower than those of modern westernised populations (Elsner, 1963). Nevertheless, prior to modernisation, individuals indigenous to cold climates were typically relatively muscular and the regional distribution of muscle and fat characteristics of these people is thought to maximise insulation (Beall and Stigmann, 2000). As pointed out by Hooton (1946), it is also perfectly possible that some human groups may have retained, or even redeveloped, body hair at a late period of human evolution.

5.4.3. Conclusions

The present study provides a comparison of regional thermal sensitivity to cold in 3 ethnic groups. The results showed significant differences and tendencies towards significance at several body sites. Most differences found were between the British and the Chinese group, with colder sensations reported by Chinese participants. The results also showed some differences between the groups in the distribution of thermal sensitivity across the body. The possibility that the greater body hair density found in the British group is one of the factors making them less sensitive was suggested. Other factors were discussed, including a reduced skin sensory nerve supply, Tsk and body fat.
Chapter 6

Study 5: Upper and lower body distribution of thermal sensitivity to cold – The effects of gender

6.1. Chapter summary

In this chapter, body maps of thermal sensitivity to cold in females were created. Additionally, a comparison with the Caucasian male participants from study 4 is also provided. The results showed that despite a similar pattern in thermal sensitivity to cold across the body, transient and steady-state thermal sensations were respectively 0.8 and 1.2 units colder in females than males. Specifically, the differences were most strongly pronounced at the central abdomen, lateral lower back and anterior thigh. Several suggestions were made in an attempt to explain the results found, including differences between men and women in the following factors: body fat levels and distribution, pre-stimulus $T_{sk}$, skin thickness, thermoreceptors distribution, hair density, menstrual factors, and psychological characteristics. All things considered, it is likely that the complex interaction of these factors resulted in the differences between males and female in the present study.

6.2. Introduction

An extensive body of literature exists on the differences between men and women in pain sensitivity, including the use of electrical, mechanical and thermal stimuli. Considerable evidence suggests that women are more sensitive than men, with respect to both pain thresholds and pain-tolerance thresholds (for reviews see Goolkasian, 1985; Rollman and Harris, 1987; Velle, 1987; Fillingim, 2000; Rhudy and
Although the mechanisms underlying these gender differences are not fully understood, several variables have been suggested as potential causes: anxiety (Robin et al., 1987), gender-role expectation (Otto and Dougher, 1985) and gender hormones (Velle, 1987). Other authors have attributed the gender differences to anthropometric and body composition factors such as body surface area and skin thickness (Larkin et al., 1986; Arendt-Nielsen and Bjerring, 1988; Lautenbacher and Strian, 1991).

In contrast, ambiguous results have been obtained on the differences between genders in thermal sensitivity to innocuous stimuli. Several authors found no gender differences in absolute thermal thresholds (temperature at which warmth/cold is initially sensed) measured at various anatomical sites (Gray et al., 1982; Lautenbacher and Strian, 1991; de Neeling et al., 1994), while others found that female individuals were more sensitive to cold and warm stimulation than males as shown by smaller thermal threshold values (Meh and Denišlič, 1994; Liou et al., 1999; Golja et al., 2003). As well as differences in thermal thresholds, gender differences have also been investigated with a method of magnitude estimation (how strong is the feeling of warmth or cold). Beshir and Ramsey (1981) compared males’ and females’ thermal sensations resulting from whole-body exposure to difference ambient temperatures. Results showed that females’ thermonutral ambient temperature was higher than that of males, suggesting a greater sensitivity to cold in females. Gender effects have also been studied at a local level; Sarlani et al. (2003) investigated perceived thermal intensity, pleasantness and pain intensity of female and male participants immersing their hands in water baths maintained at temperatures ranging from 10 to 47°C. No statistically significant difference was found in thermal intensity ratings between females and males, although women perceived the more extreme temperatures as more painful and more unpleasant than men did. Moreover, Harju (2002) investigated perceived intensity in response to cold stimuli between 10 and 33°C in men and women, at 4 body sites: upper arm, thenar, knee and foot. Results suggested that women are more sensitive at the knee and foot, but not at the thenar or upper arm.
Equivocal results have thus been obtained on the effects of gender on thermal sensitivity to cold measured with a supra-threshold stimulus. Furthermore, only a few body areas have been investigated, and no comparison exists on the distribution of thermal sensitivity across the body between males and females. The aim of the present study was therefore to analyse the differences in thermal sensitivity to cold between genders, measured with a supra-threshold stimulus applied at various sites across the body surface.

6.3. Methods

The present chapter combines data from 2 studies for the analysis of the effects of gender on thermal sensitivity. The male data originates from the study described in chapter 5, and more specifically from the White British group data (10 participants). The female data was collected using the same thermal sensitivity test procedure. The methods below describe procedures used in the male testing, which was closely followed for female testing.

6.3.1. Participants

Experiments were conducted on 10 male and 14 female participants recruited from the Loughborough University student population. All participants were healthy, physically active and had no known ailments that could impact the results of the study. The subjects were asked to read the participant information sheet which informed them about the purpose and aim of the study and details of the study requirements. Participants were asked to avoid strenuous exercise and alcohol for 24 hours prior to the study. They were also requested to abstain from caffeine and food consumption during the 2 hours prior to each session.

After providing written informed consent all participants attended the laboratory on two separate occasions, with at least 48 hours between the sessions. All
procedures were in accordance with the generic protocol G10-P10 which was accepted by the Loughborough University Ethical Advisory Committee prior to the start of the study.

6.3.2. Procedures

A male experimenter tested the male group, while a female experimenter tested the female group. As well as eliminating the need for a chaperone during the tests, this also eliminates the previously suggested issue that the experimenter and participants being of opposite genders may affect the subject’s willingness to report somatosensory ratings (Meh and Denišlič, 1994). Both experimenters were trained on several occasions, specifically on the anthropometric measurements and on the thermal sensitivity test to ensure the procedures were identical.

6.3.2.1. Pre-experimental test

Upon arrival at the laboratory, the participants were given a detailed explanation on the testing procedures. They then completed a health questionnaire and provided informed consent. For the female group, the thermal sensitivity test was performed irrespective of the menstrual cycle phase, although the participants reported the menstrual phase they were currently in.

The first session consisted of the same anthropometric measurements and sub-maximal test as described in chapter 2. Specifically, the following anthropometric measurements were taken: height, weight, and skinfolds thicknesses. These were taken using the 7-point calliper method (Jackson and Pollock, 1980) specific to female population for calculation of body fat percentage (BF%). In preparation to the experimental sessions, participants were subsequently familiarised with the testing procedures. They were given a detailed description of the procedures which would be used in the following session, and participants practiced to rate their
thermal cold sensation while stimuli of different temperatures were applied on their skin at various body sites. Participants verbally rated their thermal cold sensation immediately after contact with the probe (transient sensation), as well as 10 seconds after contact started (steady-state sensation).

6.3.2.2. Experimental session

Upon arrival in the laboratory for the second session, participants were given a description of the experimental session. They changed into their own shorts, bra, socks and trainers. They were then asked to lie on a medical bench while the investigator marked each of the testing sites on their skin. A dot of approximately 1 cm diameter was drawn in the middle of the stimulus site. Because this experiment was done at rest and during exercise, the body sites on the foot were not included (to avoid the discomfort of cycling barefoot). Sites number 15 and 27 from chapter 5 were thus not included in the present study, leaving 25 body sites in common between the two studies for the male-female comparison (Figure 6.1).

Figure 6.1 Body sites names and location in the gender comparison.
Following careful instruction, each participant inserted a rectal thermometer (Grant Instruments, Cambridge, England) 10 cm beyond the rectal sphincter for measurement of core temperature ($T_c$) during the experiment. This was only the case in the female group since core temperature was measured orally in the male group, as described in chapter 5. Pre-test body mass was then recorded using a calibrated Mettler ID1 Multirange electronic scale (Mettler Toledo, Leicester, UK; resolution = 0.001 kg). Four skin thermistors (Grant Instruments, Cambridge, England) were attached with Transpore surgical tape (3M Healthcare, USA) to the upper arm, chest, thigh and calf for measurement of $T_{sk}$ and calculation of mean $T_{sk}$ using Ramanathan’s weighing formula (Ramanathan, 1964). Skin and rectal temperature (female group only) sensors were plugged onto an Eltek/Grant 10 bit, 1000 series data logger (Grant Instruments, Cambridge, England) recording temperature at 2 second-intervals.

After preparation, participants were taken to the laboratory ($T_a$ = 21°C; $Rh$ = 40%). Room ambient temperature and relative humidity were measured using a Vaisala HMP35DGT sensor (Vaisala, Helsinki, Finland) and recorded at 1 minute intervals using an Eltek/Grant 10 bit, 1000 series squirrel data logger (Grant Instruments, Cambridge, England). They then sat on the cycle ergometer (Lode Excalibur, Groningen, Netherlands).

The initial part of the test consisted of a 10 minutes $T_c$ and $T_{sk}$ stabilisation period during which participants remained seated. A series of practice tests consisting of cold stimulus applications and thermal cold sensation ratings were done during the initial part of the temperature stabilisation period, identical to the practice session done during the pre-experimental test session. This was done to ensure that all participants were thoroughly familiarised with thermal sensitivity test prior to the thermal sensitivity test commencement.

At the start and end of the test, a reference temperature was measured on a black mat surface with the non-contact IR thermometer (Fluke 566, Washington, USA) with emissivity set at 0.98. A calibrated thermistor was taped to the black mat surface to allow correction of the $T_{sk}$ IR thermometer measurement. $T_{sk}$ was then
measured at the stimulus site with the IR thermometer held approximately 30cm from the skin. Once $T_{sk}$ had been recorded, the 25 cm$^2$ thermal sensitivity tester (NTE-2, Physitemp instruments Inc., USA) set at 20°C was placed directly onto the skin over the marked site. Although there was no systematic control of the force with which the probe was applied, an attempt was made to keep it constant throughout the study. Participants verbally rated their thermal sensation on the thermal cold sensation scale for innocuous cold stimuli, on which 0 indicates “not cold” and 10 “extremely cold”. Thermal sensation was reported immediately after contact between the probe and the skin (“transient”) as well as after 10 seconds of stimulus (“steady-state”). Time between initial contact with the skin and asking for the participant to rate his sensation again was measured with a stop watch constantly in sight of the investigator. To avoid an effect of surprise on the initial thermal cold sensation, the location of the site of stimulation was given as a warning prior to stimulus of each out-of-sight body site (e.g. “lateral lower back”). The site was then re-warmed with a hand warmer for 15 seconds, and the process was started again with the following body site. All sites were tested in a balanced order.

6.3.3. Data analysis

As explained above, the female data (14 participants) were compared with the Caucasian male data from chapter 5 (10 participants). Pre-stimulus $T_{sk}$ was corrected according to the difference found between the temperature indicated by the calibrated thermistor and the IR thermometer. Differences in pre-stimulus $T_{sk}$ were analysed with a mixed design ANOVA (gender * body site).

For an easier visual comparison of the different sites, body maps of sensitivity were developed with a scale consisting of 8 levels with a different colour being attributed to each level. This was done based on the assumption that no differences exist between left- and right hand side of the body (e.g.: Claus et al., 1987; Meh and Denišlič, 1994).
The use of an Analysis of Covariance (ANCOVA) at each body site was considered, in order to control the effect of pre-stimulus $T_{sk}$ on thermal sensation. However, an ANCOVA would effectively adjust the thermal sensation values, and would therefore potentially mask some of the differences in absolute thermal sensations between genders. Considering that the present research is performed with practical applications in mind, it was decided to compare the male and female data without the use of a covariant. A Mixed Design ANOVA was therefore used with time (transient - steady-state) and body site (25 levels) as within-subject factors, and gender as between-subject factor. The results suggested a significant interaction effect of time and gender, $F(1, 22) = 5.40; p = 0.030$ and it was therefore decided to perform a separate Mixed Design ANOVA for the transient and steady-state thermal sensation. For that same reason, both transient and steady-state thermal sensitivity body maps are presented.

The effect of gender on thermal sensation at each body site was analysed with a series of independent t-tests. With 25 sites being compared between the 2 genders, multiple post-hoc comparisons are made with the risk of inflating type I error. This matter has been discussed in the literature (Bender and Lange, 1999; Perneger, 1998). Based on these discussions, it was decided that a Bonferroni would be overly conservative (pushing the limit $P$ value for significance to 0.002 for genders) for the present type of exploratory study, and would dramatically inflate type II error. It was therefore decided to provide the significant differences and trends ($0.05 \leq p \leq 0.1$) before correction for multiple comparisons and bring to the reader’s attention that these should be interpreted with multiple comparisons in mind (Havenith et al., 2008).

The effects of skinfolds on thermal sensitivity to cold was also analysed with Pearson’s $r$ correlation coefficients (between-subjects and between-region).

Statistical analysis was performed using IBM SPSS Statistics (version 19.0, Chicago, USA). The level of statistical significance was set at $p < 0.05$ for all statistical tests.
6.4. Results

6.4.1. Participants’ characteristics

Participants’ characteristics can be found in Table 6.1. Eight of the female participants were in the follicular menstrual phase, and 6 were in the luteal phase. The female group were significantly younger, shorter and had a greater BF % than the male group (p < 0.05). Females were also lighter than males, although this difference did not quite reach significance (p = 0.055). $T_c$ was significantly higher in the female group.

Table 6.1  Participants’ characteristics. A significant difference with males is indicated by * (p < 0.05), or *** (p < 0.001)

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>23.0 ± 3.6</td>
<td>20.3 ± 1.3*</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.81 ± 0.08</td>
<td>1.73 ± 8.0***</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>73.9 ± 8.1</td>
<td>66.5 ± 9.0</td>
</tr>
<tr>
<td>BF %</td>
<td>7.4 ± 2.1</td>
<td>21.6 ± 3.1***</td>
</tr>
<tr>
<td>Σ 7 skinfolds (mm)</td>
<td>60.3 ± 10.3</td>
<td>97.5 ± 17.2***</td>
</tr>
<tr>
<td>$T_c$ (°C)</td>
<td>37.16 ± 0.26</td>
<td>37.42 ± 0.30*</td>
</tr>
</tbody>
</table>

Mean skinfolds at each body site, and sum of 7 skinfolds are presented for both genders in Table 6.2.

Table 6.2  Mean and SD of skinfold thicknesses at 8 body sites. The p-values show the difference between male and female before Bonferroni correction for multiple comparisons.

<table>
<thead>
<tr>
<th></th>
<th>Chest</th>
<th>Triceps</th>
<th>Biceps</th>
<th>Abdomen</th>
<th>Mid-axillary</th>
<th>Supra-iliac</th>
<th>Sub-scapular</th>
<th>Thigh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male mean</td>
<td>6.1±1.5</td>
<td>8.3±2.1</td>
<td>3.9±0.8</td>
<td>11.2±3.1</td>
<td>7.4±1.3</td>
<td>6.9±1.2</td>
<td>9.4±1.9</td>
<td>11.0±3.1</td>
</tr>
<tr>
<td>Female mean</td>
<td>8.3±3.2</td>
<td>17.4±4.1</td>
<td>14.4±4.8</td>
<td>16.6±4.9</td>
<td>11.3±3.1</td>
<td>12.9±4.7</td>
<td>12.7±4.7</td>
<td>18.3±3.7</td>
</tr>
<tr>
<td>p-value</td>
<td>0.007</td>
<td>&lt;0.0005</td>
<td>&lt;0.0005</td>
<td>0.0007</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.006</td>
<td>&lt;0.0005</td>
</tr>
</tbody>
</table>
6.4.2. Core and Skin temperature

As expected, $T_c$ remained stable in both groups during the thermal sensitivity test. Mean $T_c$ of the female group is presented in figure 6.2a. Mean values were 37.43 ± 0.21°C at the onset of the experiment and 37.41 ± 0.18°C at the end of the test. As described in the methods, $T_c$ was measured orally at the beginning and end of the test in the male group. Initial and end mean $T_c$ were respectively 36.88 ± 0.26°C and 36.79 ± 0.14°C. $T_c$ at the start and end of the test were both significantly greater in the female group ($p < 0.01$) but did not significantly change during the thermal sensitivity test in either group ($p > 0.05$).

![Female group $T_c$ (n = 14)](image)

6.2a Mean core temperature of the female group during the thermal sensitivity test

The ANOVA showed a significant main effect of body site on pre-stimulus $T_{sk}$, $F(24,528) = 34.10; p < 0.0005$. A main significant effect of gender on pre-stimulus $T_{sk}$ was also found, $F(1,22) = 33.25; p < 0.0005$ with females’ pre-stimulus $T_{sk}$ being lower than males’ (mean difference = 1.28°C). Finally, a significant interaction effect (body site * gender) on pre-stimulus $T_{sk}$ was also found, $F(24, 528) = 6.27; p < 0.0005$. All $T_{sk}$ mean values are presented in 6.2b.
Figure 6.2b Pre-stimulus skin temperature at each body site (means of each gender)
6.4.3. Thermal sensation

Transient and steady-state mean thermal sensations are presented in Figure 6. A-D.

6.4.3.1. Transient thermal sensation

The Mixed ANOVA revealed a significant main effect of body site, \( F(24, 187) = 14.17; p < 0.0005 \) but no significant site * gender interaction effect, \( F(24, 187) = 1.22; p = 0.219 \). Regarding the between groups analysis of gender, females reported thermal sensations which were on average 0.8 units colder than males. This difference did not quite reach significance despite a tendency for the female group to be more sensitive than the males, \( F(1, 22) = 3.10; p = 0.093 \).

6.4.3.2. Steady-state thermal sensations

The Mixed ANOVA revealed a significant main effect of body site, \( F(24, 195) = 16.74; p < 0.0005 \) as well as a significant site * gender interaction effect, \( F(24, 195) = 2.08; p = 0.002 \). Regarding the between subjects analysis, a significant effect of gender was found, with females reporting colder sensations than males by an average of 1.2 thermal sensation units, \( F(1, 22) = 5.77; p = 0.025 \).

6.4.3.3. Gender effect at individual body sites

The pairwise comparisons revealed 23 significant differences and tendencies towards significance (Table 6.3). Only six of these differences occurred in the transient, and 17 were in steady-state. Thermal sensation was colder in the female group in each case, and the difference was strongest at the central abdomen, lateral lower back and anterior thigh.
Table 6.3  Significant differences and trends (0.05 ≤ p ≤ 0.1) between genders. *Trend before Bonferroni correction. ˠ Significant difference before Bonferroni correction. ¥ Significant difference after Bonferroni.

<table>
<thead>
<tr>
<th>Body site</th>
<th>Mean Difference (male - female)</th>
<th>Transient (T) - Steady-state (SS)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Forehead</td>
<td>-1.2*</td>
<td>SS</td>
<td>.090</td>
</tr>
<tr>
<td>2 - Cheek</td>
<td>-1.4*</td>
<td>SS</td>
<td>.067</td>
</tr>
<tr>
<td>4 - Central chest</td>
<td>-1.6 ˠ</td>
<td>SS</td>
<td>.014</td>
</tr>
<tr>
<td>5 - Lateral chest</td>
<td>-1.1 ˠ</td>
<td>SS</td>
<td>.038</td>
</tr>
<tr>
<td>6 - Central upper abdomen</td>
<td>-1.8 ˠ</td>
<td>T</td>
<td>0.037</td>
</tr>
<tr>
<td>6 - Central upper abdomen</td>
<td>-1.4 ˠ</td>
<td>SS</td>
<td>.049</td>
</tr>
<tr>
<td>7 - Lateral upper abdomen</td>
<td>-1.2*</td>
<td>T</td>
<td>0.083</td>
</tr>
<tr>
<td>7 - Lateral upper abdomen</td>
<td>-1.2*</td>
<td>T</td>
<td>0.083</td>
</tr>
<tr>
<td>8 - Central lower abdomen</td>
<td>-2.1 ˠ</td>
<td>SS</td>
<td>.006</td>
</tr>
<tr>
<td>9 - Lateral lower abdomen</td>
<td>-1.0 ˠ</td>
<td>SS</td>
<td>.050</td>
</tr>
<tr>
<td>10 - Anterior upper arm</td>
<td>-1.6 ˠ</td>
<td>SS</td>
<td>.011</td>
</tr>
<tr>
<td>12 - Palmar hand</td>
<td>-1.9 ˠ</td>
<td>SS</td>
<td>.032</td>
</tr>
<tr>
<td>13 - Anterior thigh</td>
<td>-1.4*</td>
<td>SS</td>
<td>.063</td>
</tr>
<tr>
<td>18 - Central upper back</td>
<td>-1.2 ˠ</td>
<td>SS</td>
<td>.037</td>
</tr>
<tr>
<td>19 - Lateral middle back</td>
<td>-1.4 ˠ</td>
<td>SS</td>
<td>.037</td>
</tr>
<tr>
<td>20 - Central middle back</td>
<td>-1.0 ˠ</td>
<td>SS</td>
<td>.041</td>
</tr>
<tr>
<td>21 - Lateral lower back</td>
<td>-2.1 ˠ</td>
<td>SS</td>
<td>.004</td>
</tr>
<tr>
<td>22 - Central lower back</td>
<td>-1.1 ˠ</td>
<td>SS</td>
<td>.034</td>
</tr>
<tr>
<td>24 - Posterior lower arm</td>
<td>-1.9 ¥</td>
<td>T</td>
<td>0.01</td>
</tr>
<tr>
<td>26 - Posterior middle thigh</td>
<td>-2.2*</td>
<td>SS</td>
<td>.000</td>
</tr>
<tr>
<td>25 - Dorsal hand</td>
<td>-1.2*</td>
<td>T</td>
<td>0.068</td>
</tr>
</tbody>
</table>
Figure 6.3 A & B  Mean values of transient thermal sensation at each tested body site. S-S indicates steady-state sensations.
Figure 6.3 C & D Mean values of steady-state thermal sensation at each tested body site. S-S indicates steady-state sensations.
6.4.4. Skinfold thicknesses

No significant correlation was found in the analysis of the effects of skinfold thicknesses on thermal cold sensation, although a trend towards a negative correlation was found at the abdomen in the female group (p = 0.072). The correlations for each gender and for both genders combined are listed in Table 6.4 and illustrated in Figure 6.4. Finally, the within-subjects analysis (comparison of site) also showed no significant correlation between thermal sensation and skinfold thickness (r = -0.290; p = 0.243).

<table>
<thead>
<tr>
<th>Body site</th>
<th>r value (males)</th>
<th>p value (males)</th>
<th>r value (females)</th>
<th>p value (females)</th>
<th>r value (combined)</th>
<th>p value (combined)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest</td>
<td>0.186</td>
<td>0.585</td>
<td>0.35</td>
<td>0.22</td>
<td>0.281</td>
<td>0.173</td>
</tr>
<tr>
<td>Triceps</td>
<td>-0.372</td>
<td>0.26</td>
<td>0.028</td>
<td>0.924</td>
<td>-0.129</td>
<td>0.537</td>
</tr>
<tr>
<td>Biceps</td>
<td>-0.249</td>
<td>0.46</td>
<td>0.193</td>
<td>0.509</td>
<td>0.304</td>
<td>0.140</td>
</tr>
<tr>
<td>Abdominal</td>
<td>0.044</td>
<td>0.898</td>
<td>-0.495</td>
<td>0.072</td>
<td>0.099</td>
<td>0.637</td>
</tr>
<tr>
<td>Mid-axillary</td>
<td>0.205</td>
<td>0.545</td>
<td>-0.108</td>
<td>0.713</td>
<td>0.115</td>
<td>0.585</td>
</tr>
<tr>
<td>Supra-iliac</td>
<td>0.195</td>
<td>0.565</td>
<td>0.075</td>
<td>0.799</td>
<td>0.123</td>
<td>0.557</td>
</tr>
<tr>
<td>Subscapular</td>
<td>0.165</td>
<td>0.627</td>
<td>-0.018</td>
<td>0.951</td>
<td>-0.149</td>
<td>0.478</td>
</tr>
<tr>
<td>Quadriceps</td>
<td>0.015</td>
<td>0.966</td>
<td>-0.103</td>
<td>0.726</td>
<td>0.278</td>
<td>0.179</td>
</tr>
</tbody>
</table>
Figure 6.4 (A-D) Correlations between thermal sensation and skinfold thickness at each body location.
Figure 6.4 (E-H) Correlations between thermal sensation and skinfold thickness at each body location.
6.5. Discussion

Equivocal results exist on the effects of gender on thermal sensitivity. Moreover, most previous studies used a measurement of thermal threshold, and thermal sensation intensity data of males and females are limited. The present study therefore aimed to analyse the differences in thermal sensitivity to cold between genders, measured with a supra-threshold stimulus applied at various body sites across the body surface. In the present study, a thermally sensitive body site was defined as one with a great thermal cold sensation score in response to the 20°C thermal stimulus. Core temperature was measured in both groups, although the measurement method was different. This was due to the data emerging from two different studies, one of which only focusing on rest which therefore did not require $T_c$ being measured throughout the test (male data). As described in chapter 1, $T_c$ varies according to the measurement site and a male-female comparison is therefore not ideal in the present study. However $T_c$ was measured principally to ensure that no change occurs during the thermal sensitivity test. This was the case, as no significant difference was found between $T_c$ at the onset and at the end of the experiment in either group.

Looking at the overall pattern of thermal sensitivity to cold, the present results are in line with studies 3 and 4, confirming the distribution of thermal sensitivity to cold previously found in Caucasian males, this time in Caucasian females. More specifically, thermal sensitivity to cold was highest at the lateral abdomen for both groups, followed by the lateral mid-back regions. In contrast, particularly low levels of thermal sensitivity to cold were found at the hand and forearms, as well as the anterior calf. The female data also showed a relatively high level of sensitivity to cold at the central back region, as well as anterior and posterior areas of the thighs.

Despite a similar general pattern across the body, the present results showed that females reported significantly colder sensations than males in steady-state, while only a tendency towards the same effect was found in the transient. Looking at individual body sites, females reported significantly colder steady-state thermal
sensations before Bonferroni correction at 14 body sites with a further 4 showing a trend towards significance, while only 2 body sites were significantly different in the transient with another 2 showing trends towards significance. The present results therefore suggest that females generally show a stronger response to cold, particularly in terms of steady-state thermal sensation, although a larger sample might have helped some of the trends to reach statistical significance.

Regarding the distribution of the effect, the greatest male-female differences were found at the posterior middle thigh, lateral lower back, and central lower abdomen. In these regions, female participants reported thermal sensations more than 2 units colder than males. In contrast, thermal sensations were equal or almost equal between genders at the lateral anterior neck, calf and dorsal hand. Such regional inconsistencies in the gender effect has been previously reported. Harju (2002) tested innocuous and noxious thermal sensitivity to cold and warmth at 4 body sites, using a magnitude estimation method. Harju’s results showed no gender effect at the thenar or the knee, while men reported higher perceived intensity of noxious cold stimuli at the upper arm. In contrast, women were more sensitive to cold at the foot. Harju (2002) also investigated the discriminative aspect of thermal sensitivity with the method of limits, and found that cold thresholds were higher (i.e. lower discriminative thermal sensitivity) for women at the thenar, while no gender differences were found at the upper arm, foot or knee. Conversely, Liou et al. (1999) observed lower cold and warm thresholds (i.e. higher discriminative thermal sensitivity) in females than males on the hand, while no difference existed on the foot. Finally, Meh and Denišlič (1994) reported that thermal limens\(^1\) were smaller in females than males at the thenar, forearm, upper arm, thigh, calf and dorsal foot. This can be interpreted as a higher discriminative thermal sensitivity in the female group, although warm and cool perceptual thresholds were not reported individually. No differences in thermal limens were however found at the face, thorax and abdomen.

The greater thermal sensitivity to cold found in females in the present study at several body sites may be attributed to several physiological and morphological

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\(^1\) Thermal limen: temperature difference between warm and cool thermal thresholds
differences between genders. The lack of any significant negative correlations between thermal sensation and skinfold thickness suggests that body fat may not be a factor that plays a role in thermal sensitivity to cold. However a trend towards a negative significant correlation was found in the female group at the abdomen (p = 0.072), suggesting that in that group larger skinfold thicknesses may be associated with lower thermal sensitivity to cold. This would be in agreement with Glickman-Weiss et al. (1998) who found that during exposure to a 5°C environment for 120 min, females with low body fat percentage perceived colder whole-body thermal sensations than their high body fat percentage counterparts. These differences in thermal sensation were found despite a lack of significant differences in mean skin temperature between the groups. However it must be noted that the trend found at the abdomen in the female group disappeared when analysing correlations with all data (male and female) combined. The exact mechanisms by which a greater layer of body fat may result in a lower thermal sensitivity remain unclear. Although Gickman-Weiss et al.’s results suggest otherwise, one possible explanation may be the effect of body fat on $T_{sk}$, which in turn may have an impact on thermal sensitivity. In the present study, body fat percentage was greater in females than males, which may explain the significantly lower pre-stimulus $T_{sk}$ in females compared with males. In theory, having a colder $T_{sk}$ results in skin being effectively stimulated with a lower $\Delta T$, and this in turn is expected to result in a less intense thermal sensation. This effect of pre-stimulus $T_{sk}$ would only be expected in the transient but not in steady-state. Less intense thermal sensations were however not found in females, suggesting that other mechanisms may have a greater impact than pre-stimulus $T_{sk}$ in explaining the differences found between genders. However, it must be noted that the gender effect was least pronounced in the transient, which may indicate that the lower pre-stimulus $T_{sk}$ found in the female group reduced the gender effect in the transient.

Differences in the density of thermoreceptors are likely to play a major role in thermal sensitivity differences between genders. Using 3mm punch biopsies, Gøransson et al. (2004) analysed the epidermal nerve density at the lower leg of males and females, and found that the density of epidermal nerve fibres is
significantly greater in women compared with men. It is widely accepted that thermoreceptors distribution varies across the body (e.g. Strughold and Porz, 1931), and it is possible that this regional distribution varies between genders, although no study has systematically investigated thermoreceptors distribution across the body in males and females. Moreover, Furthermore, morphological factors such as hair density may also explain some of the differences found. The present results suggest that the largest differences in thermal sensitivity between genders are at the abdomen, posterior lower arm and anterior thigh. Although the female group in the present study was not analysed for hair density, these sites coincide with body areas which are naturally more hairy in men than women. Men’s hair may have therefore acted as an insulator for the skin, introducing thermal resistance between the stimulus (thermal probe) and the skin. This would not be the case in the female participants who do not tend to have abdominal hair and usually shave their legs. Hair distribution and shaving have been previously mentioned as potential factors playing a role in the genders differences in thermal and pain sensitivity (Caissie et al., 2007). Furthermore, skin thickness may also be a factor involved in the trend towards a greater sensitivity in the female group (Golja et al., 2003). Indeed, it has been shown that females’ skin is thinner than that of males (Sandby-Moller et al., 2003). It is therefore possible that males’ thicker skin act as a barrier between the thermal stimulus and the thermoreceptors, thereby reducing the intensity with which these are essentially stimulated. Skin thickness has previously been suggested as an influential factor in male-female thermal sensitivity comparisons.

In addition, the differences in thermal sensitivity to cold between males and females could perhaps be explained on the basis of previous observations in another cutaneous sensory system such as pain. Indeed, it has been suggested that biological factors, such as menstrual phase, dysmenorrhea\(^2\) status and tissue depth may have unique interacting effects on pain thresholds (Giamberadino et al., 1997). Due to the applied nature of the current project, it was decided not to analyse the data according to menstrual phase. This would however be a relevant factor to investigate in future research. Finally, psychosocial factors such as gender role

\(^2\)Dysmenorrhea: gynaecological medical condition of pain during menstruation
beliefs, pain coping strategies, mood and pain-related expectancies have been suggested as potential factors explaining gender differences in pain sensitivity (Filligrim, 2000). There is also evidence that familial factors can alter pain responses and these intergenerational influences may differ as a function of gender. Although difficult to demonstrate in the present context, some of these factors may also partially mediate the gender differences found in the present study.

6.5.1. Conclusions

The present study aimed to analyse the differences in thermal sensitivity to cold between genders, measured with a supra-threshold stimulus applied at various body sites across the body surface. The results showed that despite a similar pattern in thermal sensitivity to cold across the body, transient and steady-state thermal sensations were respectively 0.8 and 1.2 units colder in females than males. While an overall significant effect was found in the steady-state, the differences were not of great magnitude and only the stronger effects may be relevant for practical applications. Specifically, the differences were most strongly pronounced at the central abdomen, lateral lower back and anterior thigh. Several suggestions were made in an attempt to explain the results found, including differences in men and women in the following factors: body fat levels and distribution, pre-stimulus T_{sk}, skin thickness, thermoreceptors distribution, hair density, menstrual factors, and psychological characteristics. All things considered, it is likely that the complex interaction of these factors resulted in the differences between males and female across the body found in the present and previous studies.
Chapter 7

Conclusions and Applications of Research

As described in the introduction chapter, several gaps exist in the current knowledge related to thermal sensitivity to cold. These can be grouped in two broad topics:

- The distribution of thermal sensitivity to cold across the human body
- The effects of exercise on thermal sensitivity to cold

In the present research project, five experimental studies aimed to provide answers to several research questions related to these topics. The main findings and notable points of discussion from the work conducted in this thesis are summarised in the present chapter. The potential applications of this research are also highlighted.

7.1. Final discussion and conclusions

The present project was launched by the Engineers from Oxylane Research. This company is responsible for the Research and Development activities at Decathlon, a major international sporting goods chain store manufacturing over 10 sports brands. Several main questions related to thermal sensitivity to cold were posed, and two different experimental approaches were used to answer these. In the first approach, a water-perfused suit was used to cool whole body segments individually. This allowed comparisons between the segments as well as between a resting, exercising, and recovering conditions. In the second approach, a 25 cm² thermal probe was directly applied onto the skin while participants rated their cold sensation. With this method, comparisons were made between the following:

- Transient and steady state
- Different locations within body segments across the body
- Rest and exercise
- Individuals of European, African and Asian ethnicities
- Males and females.

The final discussion and conclusions are presented in this section.

### 7.1.1. Measurement of thermal sensitivity

#### 7.1.1.1. Experimental limitations

Before the start of study 1, a bespoke cooling system was designed and built for the present project. Crucial features incorporated in the system include the use of an industrial chiller and powered pumps which respectively provide enough cooling power and water flow for substantial skin cooling, even during exercise. Additionally, the design allows different body segments of the cooling garment to be simultaneously perfused with water at different temperatures with the use of three independent water tanks.

In study 1, an attempt was made to create a dataset of skin temperature, thermal sensation and thermal comfort during the cooling of individual whole body segments, at rest and during exercise. However, experimental limitations were met, which hindered the data reliability. This allowed a better understanding of specific experimental needs in order to reliably investigate the research questions initially posed. These are the most important experimental recommendations for future studies looking at thermal sensitivity of whole body segments:

- When measuring thermal sensitivity as a change in thermal sensation per change in skin temperature ($\Delta LS/\Delta T_{sk}$), it is crucial that the total $\Delta T_{sk}$ is similar amongst all the body segments. If this is not the case, it is likely that results will be biased, and body segments which have been cooled down the least will appear to be the most sensitive while they in fact may have a low thermal sensitivity. Although this may seem logical, to the knowledge of the
author, this important rule has not been highlighted before, and previous research with a similar protocol compared thermal sensitivities at body segments using data obtained with significantly different \( \Delta T_{sk} \) (e.g.: Nakamura et al., 2008).

- When cooling the skin with a water-perfused suit, it is essential to use several measurement points for \( T_{sk} \). Indeed, results in study 1 suggested that skin temperature at the calf only decreased by 1.5°C after 9 minutes of cooling, compared to values of around 5-7°C found in other zones. However, this appeared to have been due to the consistent placement of the skin thermistor under an area not fully covered by tubes. As a result, \( T_{sk} \) was measured at 4 sites on each cooled segment in study 2 which allowed for a reliable measurement of the whole segment mean \( T_{sk} \).

- Additionally, pilot tests before the start of study 2 highlighted several advantages which wireless iButtons have over thermistors for the measurement of \( T_{sk} \) under a water-perfused suit. These are have the benefit of being wide, making them less likely to fall under a non-cooled area or in-between 2 tubes. Furthermore, their thickness reduces the impact of tubes temperature on the \( T_{sk} \) measurement. This advantage related to the encapsulation of the actual sensor has been suggested previously (EMPA, personal communication). Finally, using wireless iButtons allows \( T_{sk} \) to be measured at several points without extra wires which can create issues such as tangling or pain when fitted under a tight “leotard” garment.

7.1.1.2. Different measurements of thermal sensitivity

Throughout the present thesis, different measurements of thermal sensitivity were used and referred to. As highlighted in the discussion of chapter 4, it is essential to make the difference between the ability to detect a thermal stimulus (e.g.: method of limits and cold spots body mapping) and the intensity reported after application
of a given thermal stimulus (e.g.: magnitude estimation and intensity rating with a thermal sensation scale). To the author’s knowledge, the importance of these differences had not clearly been clearly established before and previous investigators have used various methodologies and protocols for the measurement of what they all referred to as thermal sensitivity without explicitly notifying the reader of the implications which each methodology has.

This point is particularly important in the context of applied research such as the present thesis, because body sites which have a high thermal sensitivity as defined by the method of limits (i.e. low threshold for cold detection) will not necessarily have a high thermal sensitivity when measured with an intensity rating method. A good example of this divergence is shown at the forehead, which is often considered as the most sensitive area to cold (e.g.: Lee et al. 2010a) who used the method of limits, while it appears to be amongst the least sensitive sites when using an intensity rating method (e.g.: Stevens, 1979; study 4). With the clothing applications anticipated in the present project, it seemed preferable to base all thermal sensitivity measurements on methods of intensity ratings.

7.1.2. Regional differences in thermal sensitivity to cold

7.1.2.1. Distribution between body segments

In study 2, improvements made to the water-perfused suit and the protocol allowed fair comparisons of thermal sensitivity to cold at 8 whole body segments. Thermal sensitivities were calculated as a change in local thermal sensation per change in $T_{sk}$ and the average values found for each segment, from relatively sensitive to insensitive were as follows (in thermal sensation unit per °C): lower back (1.69), upper legs and upper arms (1.56), lower arms (1.51), chest, upper back (1.19), lower legs (1.17), and abdomen (0.88). These differences may reflect the existence of complex mechanism of integration at the CNS, which takes into account the surface area stimulated, the density of thermoreceptors present at each body segment, and the risk that skin cooling at that region will result in a core temperature decrease.
Furthermore, a significant correlation was found between the cold sensation and body hair density in study 3, indicating that body regions with lower levels of local hairiness were associated with greater (colder) local thermal sensations. This suggests that hair may have acted as an insulator for the skin, introducing thermal resistance between the cold stimulus and the skin. This may therefore also be a key factor in the determination of body regional differences in thermal sensitivity to cold.

Another relevant result finding in study 2 was that a body segment which has a relatively low thermal sensitivity to cold will not necessarily induce a low level of overall cold sensation, compared to other segments. For example, while the upper back has a moderate $\Delta LS/\Delta T_{sk}$ compared with other segments, it has a strong influence on overall sensation. One explanation for this difference is related to the importance of other segments which contribute to the rating of overall thermal sensation. Levels of $\Delta OS/\Delta T_{sk}$ are thought to be the result of a complex interaction between the thermal transfer dynamics and the local thermal sensitivities of each body segments.

The same is also applicable for local and overall thermal comfort. It is therefore important to carefully decide which parameter must crucially be “protected” before applying the dataset to clothing and thermal manikins. Indeed, if regional insulation levels are adapted to thermal sensitivity to cold, one must first decide whether to use $\Delta LS/\Delta T_{sk}$, $OS/\Delta T_{sk}$, $LC/\Delta T_{sk}$ or $OC/\Delta T_{sk}$. In other words, is it more important to avoid a local sensation of cold, an overall cold sensation, local thermal discomfort, or overall thermal discomfort?

Finally, Table 7.1 summarises all the thermal sensitivity values found in study 3, including $\Delta LS/\Delta T_{sk}$, $OS/\Delta T_{sk}$, $LC/\Delta T_{sk}$ or $OC/\Delta T_{sk}$ for all 3 experimental conditions.
In study 3, thermal sensitivity to cold was investigated with a 25 cm² stimulus, allowing for within-segment comparisons. Novel to the present thesis is that regional variations in thermal sensitivity were observed between sites within the same body segment. This was especially true on the abdomen, where the lateral areas were significantly more sensitive than the medial sites. No significant differences were found on the back. Regarding the arms, no significant differences were present between the anterior and posterior sites at the upper arm or forearm, but the posterior forearm was significantly less sensitive than the upper arm sites. These intra-segmental differences were confirmed in male and female Caucasian participants in studies 4 and 5. The differences found within body segment suggest that test locations chosen in earlier studies were not necessarily representative for the whole segment. The variables which are thought to cause the regional differences in thermal sensitivity are the uneven distribution of cutaneous thermoreceptors and the existence of a weighing of thermoafferent information by the integration centre in the central nervous system.
7.1.3. The effects of exercise on thermal sensitivity

While confirming the alliesthesial effect of exercise on thermal comfort during cooling, results of study 2 also showed that when an individual starts exercising from an already locally cooled state, local thermal sensation of cold will become weaker (i.e. less cold) even if skin temperature continues to drop at the cooled segment. This translated into a significantly lower thermal sensitivity to cold \((\Delta LS/\Delta T_{sk})\) during exercise, compared with the resting condition. Such a decrease in thermal sensitivity to cold has not been demonstrated previously. Similarly, a significant main effect of exercise was found in study 3, with thermal sensations in response to the cold stimuli being lower (less cold) during exercise compared with rest. Furthermore, the distribution of thermal sensitivity to cold appeared more uniform during exercise than at rest, as highlighted in the body maps created. Several contributing factors to the decrease in sensitivity were discussed in this thesis, including core and muscle temperature, as well as neural, hormonal and psychological factors. Because participants remained less sensitive to cold 15 minutes after the cessation of exercise (study 2), it was suggested that this time course was similar to that of endocrine response with a long lasting after-effect. It was therefore considered that the activation of the stress analgesia system may play a key role in the as a mechanism explaining the modulation of somatosensory sensitivity.

7.1.4. Effects of ethnicity on thermal sensitivity to cold

In study 4, limited overall differences in thermal sensitivity to cold were found between British, Chinese and Nigerian individuals. A trend was found between British and Chinese in the steady-state, with Chinese being more sensitive to cold than British as a main effect \((p = 0.063)\). However, analysing individual body areas, thermal sensations were found to be significantly colder in the Chinese group than the British in the following body sites: anterior upper arm, anterior middle thigh, dorsal foot, central middle back, and central lower back. Nigerian participants were also more sensitive than their British counterparts at the dorsal foot.
Especially large differences in thermal sensitivity were found at the extremities, and more specifically at the hand and foot, with Chinese and Nigerians reporting thermal sensations ≈ 2 units colder than their British counterparts. The results also showed some dissimilarity between the groups in the distribution of thermal sensitivity across the body. These were highlighted with the creation of full body maps of thermal sensitivity to cold for each ethnic group. The possibility that the greater body hair density found in the British group is one of the factors making them less sensitive was suggested, although several of the significant sites will have little body hair. Other factors were discussed, including a reduced skin sensory nerve supply, differences in skin temperature, and body fat distribution.

7.1.5. Effects of gender on thermal sensitivity to cold

In study 5, a comparison in thermal sensitivity to cold across the body was made between Caucasian males and females. The results showed that despite a similar pattern in thermal sensitivity to cold across the body, transient and steady-state thermal sensations were respectively 0.8 and 1.2 units colder in females than males. While an overall significant effect was found in the steady-state, the differences were not uniform across the body. Specifically, the differences were most strongly pronounced at the central abdomen, lateral lower back and anterior thigh. Several suggestions were made in an attempt to explain the results found, including differences in men and women in the following factors: pre-stimulus Tsk, skin thickness, thermoreceptors distribution, hair density, menstrual factors, and psychological characteristics. All things considered, it is likely that the complex interaction of these factors resulted in the differences between males and female across the body found in the present and previous studies.

To conclude, the flow chart in Figure 7.1 summarises all the aspects of thermal sensitivity to cold investigated in the present project, as well as the mechanisms which are thought to be behind the results found in the 5 studies presented in this thesis.
Figure 7.1. Flow chart summarising the factors affecting thermal sensitivity to cold
7.2. Applications of research

Several possible avenues exist for the direct application of the datasets created in the present PhD. Due to a strict confidentiality policy within Oxylane Research, the author himself is not fully aware of the specific products which will benefit from his research. The general idea behind this research was to adapt regional levels of clothing insulation according to local sensitivities to cold. It is important to note that the regional differences found in the present study must be applied hand in hand with Tsk data. Indeed, it would only be appropriate to provide extra protection against the cold in a thermally sensitive area if this area is subject to important drops in Tsk.

Alternatively, another possible application of the results would be the use of vents strategically located, either for avoidance of cold and uncomfortable perceptions or to the contrary, for strongest cooling sensations. Moreover, results of studies 2 and 3 may also be used for the improvement of physiological models, with the inclusion the detailed distribution of thermal sensitivity to cold across the body, as well as the specific reductions in thermal sensitivity to cold resulting from exercise. Finally, study 4 and 5 provide comparisons between members of different ethnic groups as well as between genders. These results could be used to render even more individual-specific the potential applications mentioned above.

Additionally, results of study 3 have led to the imagination of a potential application distinct from the initial objectives of the study. This is related to pre-cooling strategies, and more specifically to the cold and uncomfortable perceptions associated with pre-exercise cooling. As shown in the results, cycling at a low intensity (30% VO2 max) not only reduces the intensity of cold sensations, but also induces a shift in thermal comfort from strong negative values to positive ones. This was accompanied by an increase in Tc of only ≈ 0.1°C. Therefore, the author proposes the potential use of light exercise during skin cooling strategies, which may allow further skin cooling while minimising cold and uncomfortable perceptions. This would of course need to be tested empirically as this would be the only way to discover whether this cooling strategy may be beneficial.
Chapter 8

Recommendations for future work

The research in this thesis was of an applied and largely exploratory nature. The results from the present data give rise to further research questions which are described below.

1. Concerning regional differences in thermal sensitivity to cold, several questions remain unanswered, particularly regarding the differences found between lateral and central areas of the abdomen. It would be of great interest to investigate the distribution of cold spots within body segments, on the front torso in the first instance. Additionally, although some results of study 4 suggest the potential role of body hair, it would also be useful to systematically investigate the direct effects of body hair on thermal sensitivity to cold.

2. As suggested in chapter 3, the strong effects of exercise on thermal sensitivity to cold may be related to changes in muscle temperature. Using a similar protocol but with the inclusion of muscle temperature measurements, it would be relevant to investigate whether this factor correlate well with the effects of exercise on thermal sensitivity to cold, particularly during post-exercise recovery periods.

3. The effects of body fat on thermal sensitivity to cold are still poorly understood. Although several positive between-subjects correlations were found between skinfold thicknesses and thermal sensations, it would be useful to analyse this with participants with a wider range of body fat percentages. This may highlight stronger effects, since the majority of participants in the present thesis had a low BF%.

4. Finally, the results of study 3 may have a specific use in the context of pre-exercise cooling. This would of course need to be experimentally verified, with a comparison between a cooling strategy at rest and one during light exercise.
References


Davey, S., Reilly, T., Newton, M., & Tipton, M. (2007). The reproducibility and validity of visual analogue scales (VAS) that assess thermal perceptions in stable and


on the accuracy of mean skin temperature calculations. European Journal of Applied Physiology and Occupational Physiology, 56(1), 120-125.


Sandby-Moller, J., Poulsen, T., & Wulf, H. C. (2003). Epidermal thickness at different body sites: Relationship to age, gender, pigmentation, blood content, skin type and smoking habits. *Acta Dermatovenereologica-Stockholm, 83*(6), 410-413.


Tortora, G. J., & Derrickson, B. *Principles of anatomy and physiology*. Wiley.


Yosimura, H., & Iida, T. (1952). Studies on the reactivity of skin vessels to extreme cold. part 2. factors governing the individual difference of the reactivity, or the resistance against frost-bite. *Ipn.J.Physiol, 2,* 177-185.

Appendices

Appendix 1: Participants information sheet

A study investigating local skin sensitivity to a local cold stimulus is to be conducted as part of a PhD research project. Participants will be asked to attend the lab for one pre-test session (45min) and three test sessions (2 hours each). The pre-test session will consist of basic anthropometric measurements (i.e. height, weight, skinfolds), followed by a sub-max test, which is a progressive bicycle exercise test lasting approximately 20 minutes. On the other 3 attendances, the thermal sensitivity tests will be performed.

Core temperature will be monitored with a rectal thermometer that the participant will self-insert 8cm beyond the anal sphinter. Skin temperature will be measured with thermistors taped to the skin.

The participant will put on a water-perfused suit, which consists of a tight-fitting garment in which a network of plastic tubing is sewn. A chiller is used to cool and pump water through the suit. The test consists of cooling down and warming up different zones of the body. Using subjective scales, the participant will be asked to rate his temperature sensation and comfort of different body segments at regular intervals. At the end of the test, all the equipment will be removed from the participant.

The procedures involved in this experiment have no known risks and are listed under the University’s generic protocols. All information will be kept confidential via the allocation of reference numbers to each participant so that results and personal information can in no way be associated with a particular individual. All data collected will be securely filed in the laboratory of Loughborough University.

Also, you have the right to withdraw from the investigation at any point in time and without providing a reason. If you have any problems or queries regarding the investigation please do not hesitate to contact me via email at y.ouzzahra@lboro.ac.uk or by phone on [redacted].

Thank you for your time

Yacine Ouzzahra
Environmental Ergonomics Research Centre
Loughborough University
Appendix 2: Health Questionnaire and Consent Form

HEALTH SCREEN FOR STUDY VOLUNTEERS

It is important that volunteers participating in research studies are currently in good health and have had no significant medical problems in the past. This is to ensure (i) their own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

Please complete this brief questionnaire to confirm fitness to participate:

If YES to any question, please describe briefly in the spaces provided
(eg to confirm problem was/is short-lived, insignificant or well controlled.)

1 At present, do you have any health problem for which you are:

(Please tick as appropriate)

(a) on medication, prescribed or otherwise Yes No
(b) attending your general practitioner Yes No
(c) on a hospital waiting list Yes No

2 In the past two years, have you had any illness which required you to:

(Please tick as appropriate)

(a) consult your GP Yes No
(b) attend a hospital outpatient department Yes No
(c) be admitted to hospital Yes No
3 Have you ever had any of the following:  

<table>
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<th>Condition</th>
<th>Yes</th>
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<td>Convulsions/epilepsy</td>
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</tr>
<tr>
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<tr>
<td>Head injury</td>
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<tr>
<td>Digestive problems</td>
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<tr>
<td>Heart problems</td>
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<td></td>
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<tr>
<td>Problems with bones or joints</td>
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<td></td>
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<tr>
<td>Disturbance of balance / co-ordination</td>
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<td></td>
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<tr>
<td>Numbness in hands or feet</td>
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<td></td>
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<tr>
<td>Disturbance of vision</td>
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<td></td>
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<tr>
<td>Ear / hearing problems</td>
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<td></td>
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<td>Thyroid problems</td>
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<td></td>
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<tr>
<td>Kidney or liver problems</td>
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Optional questions for female participants  

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<th>No</th>
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<td>(a) are your periods normal/regular?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) are you on “the pill”?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c) could you be pregnant?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d) are you taking hormone replacement therapy (HRT)?</td>
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</table>
Declaration Of Consent

I, (FULL NAME) _____________________________ hereby volunteer to be an experimental subject in thermal experiments during the period of / on (DATE) ______________________

My replies to the above questions are correct to the best of my belief and I understand that they will be treated with the strictest confidence by the experimenter. The purpose of the experiment has been explained by the experimenter and I understand what will be required of me.

I understand that I may withdraw from the experiment at any time and that I am under no obligation to give reasons for withdrawal or attend again for experimentation. I also understand that the experimenter is free to withdraw me from experimentation at any time.

I undertake to obey the laboratory regulations and the instructions of the experimenter regarding safety, subject only to my right to withdraw as declared above.

Signature of Subject ______________________ Date ______________________
Signature of Experimenter ___________________ Date ______________________
Appendix 3 – Cooling patches prototype

Calculation of tubes density

Four different types of tubes were tested. Each had a different radius before it kinks, meaning that the distance between tubes (and therefore tubes density) would be different depending on which tubes are being used. Characteristics of the tubes are listed in Table A1.

Table A1 Characteristics of the selected tubes for cooling patches

<table>
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<tr>
<th>Model/material</th>
<th>Diameter internal/external (mm)</th>
<th>Thickness (mm)</th>
<th>Radius before kinking (mm)</th>
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<td>5 / 3</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Tygon R3603</td>
<td>4.8 / 3.2</td>
<td>0.8</td>
<td>27</td>
</tr>
<tr>
<td>PVC farnell</td>
<td>4.5 / 3</td>
<td>0.75</td>
<td>26</td>
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<tr>
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<td>3.2 / 1.6</td>
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<td>25</td>
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<td>4 / 2.4</td>
<td>0.8</td>
<td>23</td>
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<tr>
<td>PVC</td>
<td>4 / 2</td>
<td>1</td>
<td>17</td>
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</tbody>
</table>

For the first attempt, it was decided to use the 4 mm Tygon tubes, as it offered the second lowest radius before kinking while being a strong material. Different options also existed for the tubes’ support. The textile engineers of Oxylane Research provided a support consisting of small loops which were sown onto a rigid strap with Velcro for adjustments (FigureA1).

Figure A1. Patches’ support: prototype 1
Their conception unfortunately turned out to be time consuming, and it was decided to use a more simple method for the prototype. This consisted of simply perforating holes on elastic straps (20mm width; 20cm length) and put the tubes through them. The holes were perforated using a gas powered drill.

After considering several tubing patterns for the cooling patches, it was decided that to separate the holes on the straps by a distance equal to half the radius before kinking. Holes were perforated every 11.5mm apart on the two elastic straps. The two straps were screwed 20 cm apart and the tubes were then put through the holes. Loops were produced with the tubes going from one strap to the other. To maximise the tubing density while avoiding tube kinking, the tube went through every other hole in one direction and the same was repeated in the other direction. This first prototype is illustrated in Figure A2.

![Figure A2. Assembling of prototype 1](image)

An attempt was then made to fit the patch onto the author’s forearm, by attaching the straps around the wrist and elbow with safety pins. As illustrated in Figure 3.3a and 3b, the patch fitted well on the forearm but difficulties were however met in keeping the distribution of tubes uniform. Furthermore, some of the holes
perforated through the straps quickly stretched because of the tubes friction and were eventually damaged (Figure A3).

The former limitation was overcome by incorporating 4 holes per tube loop (instead of 2), and the latter by replacing the simple holes by consolidated ones with a plastic support around it (Figure A4).

Figure A3. Cooling patch prototype.

Figure A4. Tube loop with two consolidated holes
## Thermal Sensation Scale

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<tr>
<td>+9</td>
<td></td>
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<tr>
<td>+8</td>
<td>Very hot</td>
</tr>
<tr>
<td>+7</td>
<td></td>
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<tr>
<td>+6</td>
<td>Hot</td>
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<td></td>
</tr>
<tr>
<td>+4</td>
<td>Warm</td>
</tr>
<tr>
<td>+3</td>
<td></td>
</tr>
<tr>
<td>+2</td>
<td>Slightly warm</td>
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<tr>
<td>+1</td>
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<td>Neutral</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>-4</td>
<td>Cool</td>
</tr>
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<td></td>
</tr>
<tr>
<td>-6</td>
<td>Cold</td>
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<tr>
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</tr>
<tr>
<td>-9</td>
<td></td>
</tr>
<tr>
<td>-10</td>
<td>Extremely cold</td>
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</table>
Thermal Comfort Scale

+5  Very comfortable
+4
+3  Comfortable
+2
+1  Just comfortable
-1  Just uncomfortable
-2
-3  Uncomfortable
-4
-5  Very uncomfortable
Appendix 5: Skin temperature at non-cooled segments

- **Chest cooling**
  - Tsk (°C) vs Neutrality, End rest/Start exercise, End exercise/Start recovery, End recovery
  - Segments: Abdomen, Upper arm, Lower arm, Upper back, Lower back, Thigh, Calf

- **Abdomen cooling**
  - Tsk (°C) vs Neutrality, End rest/Start exercise, End exercise/Start recovery, End recovery
  - Segments: Chest, Upper arm, Lower arm, Upper back, Lower back, Thigh, Calf

- **Upper arms cooling**
  - Tsk (°C) vs Neutrality, End rest/Start exercise, End exercise/Start recovery, End recovery
  - Segments: Chest, Abdomen, Upper Back, Lower back, Lower arm, Thigh, Calf
Figure A5 Skin temperature at each of the non-cooled body segments throughout the experiments (n = 1)
Appendix 6: Description of the location of the tested body sites

Sites 1, 3 and 5 are situated along the mid-torso area. More specifically, the thermal stimulator is positioned so that its edge was on the straight line between the sternum and the umbilicus. These test areas were chosen because the entire probe surface could be placed in contact with the skin, which would not have been possible if the sites were across the mid-torso line.

Sites 2, 4 and 6 are on a straight line parallel to the mid-torso line described above. The distance between the two lines is equal to the space separating the umbilicus from the anterior iliac crest. Sites 2, 4, and 6 are thus respectively equidistant to 1, 3 and 5. The vertical distance between the sites was calculated as follows: site 1 is 10cm above the sternum, site 5 is at the level of the umbilicus and site 3 is the mid-point between the two.

A similar approach was used for the back sites; 8, 10 and 12 are positioned along the spine, with the thermal stimulator’s edge placed on the exterior of the vertical line of the spine. Sites 7, 9 and 11 are on a straight line parallel to the line across the middle of the back described above. The vertical distance between the two lines is equal to the space separating the lumbar spine and the posterior iliac crest. Vertically, the sites’ positions are defined according to the following criteria: 7 is at the top of the scapula; 11 is at the level of the posterior iliac crest, and 9 is the mid-point between the two.

Sites 13 and 14 are at the level of the mid-point between the acromial process and the elbow joint; 13 is on the mid-line of the anterior surface of the arm (over the biceps muscle) and 14 is on the mid-line of the posterior surface of the arm (over the triceps muscle).

Finally, sites 15 and 16 are at the level of the mid-point between the wrist and the elbow joint, with 15 being on the anterior surface and 16 on the posterior surface or the forearm.
## Appendix 7: Skinfold thicknesses (study 3)

Table A2  Local skinfold thicknesses - Raw data

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<th>Biceps</th>
<th>Abdominal</th>
<th>Suprailiac</th>
<th>Subscapular</th>
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</table>
### Appendix 8: Hairiness (study 4)

Table A3  Individual participants' local and total hairiness levels. 5-point scale (0 to 4), such that a score of 0 = the absence of hairs, a score of 1 = minimally evident hair growth and a score of 4 = extensive hair growth (Garn, 1951)

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<th>Up_arm</th>
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<th>med_abs</th>
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<th>med_chest</th>
<th>lower_leg</th>
<th>upper_leg</th>
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